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LINK PERFORMANCE ANALYSIS OF A SHIP-TO-SHIP LASER COMMUNICATION SYSTEM

by

Ang Toon Yiam Ronny

March 2012

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LINK PERFORMANCE ANALYSIS OF A SHIP-TO-SHIP LASER COMMUNICATION SYSTEM

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ABSTRACT

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LIST OF ACRONYMS AND ABBREVIATIONS

ATP	Acquisition, Tracking and Pointing
BER	Bit Error Rate
BW	Bandwidth
EA	Electro-absorption
EMC	Electromagnetic Compatibility
EMI	Electromagnetic Interference
FSO	Free Space Optical
FSOC	Free Space Optical Communication
HERO	Hazards of Electromagnetic Radiation to Ordnance
ISI	Inter Symbol Interference
LEDs	Light Emitting Diodes
LO	Local Oscillator
LOS	Line of Sight
LPD	Low Probability of Detect
LPI	Low Probability of Intercept
MOP	Measure of Performance
MRR	Modulating Retro-Reflector
MZ	Mach-Zehnder
NEP	Noise Equivalent Power
PC	Photoconductive
PE	Photoemissive
PV	Photovoltaic
RF	Radio Frequency
RMS	Root Mean Square
SNR	Signal to Noise Ratio
UAV	Unmanned Aerial Vehicle

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I. INTRODUCTION

The first chapter of the thesis covers the background information about the research topics in laser communications (lasercom) and highlights the benefits of the research. In addition, this chapter also presents the research questions to be answered and explains the approach to arriving at the answers.

A. BACKGROUND

As the availability of frequency spectrum becomes scarce and the need for highly secured communications becomes increasingly crucial, lasercom presents an appealing alternative to radio frequency (RF) communications. Gigabits of information can be transmitted per second via lasercom. The high directionality of the laser also makes it an excellent medium for communications as it eliminates mutual interference issues such as intermodulation, out-of-band emissions, receiver desensitization, etc., faced by RF communications and minimizes the probability of transmission intercept and detection (Mawrey 2011; Li 2009).

The benefits of high data rates, high directionality, low sidelobes, small size, lightweight, and low power make lasercom an attractive option for ship-to-ship communications. Missions that involve the use of ship-to-ship communications depend critically on the link performance. Link performance is measured in terms of the probability of receiving messages transmitted by the laser beam, and it is usually determined by the link budget analysis.

Link budget analysis refers to the study of all the gains and losses that a signal would experience as it is being embedded in a laser beam and transmitted by the transmitter, propagating through the transmission medium and eventually being intercepted at the receiver. The link budget is highly dependent on equipment performance, weather conditions, and modulation techniques. The ability of a communication system to provide an overall gain such that the signal could be effectively received at the receiver is the ultimate objective of link budget analysis. By analyzing the link budget, the link performance would be known, which would aid in the formulation of the system requirements.

The link budget is highly dependent on the maritime environment conditions (atmospheric and water surface conditions) and also to the ship-to-ship relative motion. The high humidity of a maritime environment causes laser beam scattering and absorption and thereby affects laser beam propagation. The severe atmospheric turbulence in a maritime environment also affects the laser beam propagation (Toselli 2010). In addition, extreme weather conditions, which are uncontrollable, such as fog, heavy rain and snow would adversely affect the link performance. As such, it is essential to cater link margin in the link budget to offset this degradation effect. The link margin is the difference between the signal power and the minimum input signal power required by a receiver to produce a specified desired output. The required high directionality and narrow beamwidth of a laser beam also impose challenges on the acquisition, tracking, and pointing (ATP) system (Neo 2003). It is crucial to identify all the internal and external elements that could constructively or adversely affect the link performance and to treat them accordingly in order to bring about effective laser communications that satisfy the mission requirement.

The objective of this research is to provide insights into effects of maritime environment on lasercom link budget, thereby supporting ship-to-ship lasercom system design and mission planning. It also aims at identifying the lasercom system design parameters that are required to meet specific ship-to-ship lasercom requirements.

B. RESEARCH QUESTIONS

This research attempts to answer the following questions:

1. What are the maritime environmental conditions (atmospheric and water surface conditions) that affect lasercom link performance?
2. How is link budget calculated for lasercom in a maritime environment?

3. What are the lasercom system design parameters that can be determined in order to meet ship-to-ship lasercom requirements?

C. APPROACH

The approach to answering the questions posed immediately above involves the following steps:

1. Investigating, through literature view, the basic structure of lasercom systems, effects of maritime environmental conditions on laser communications, link budget parameters and calculation methods, lasercom signal-to-noise ratio (SNR), bit-error rate, modulation techniques, acquisition, tracking, and pointing (ATP) systems, and adaptive optics.

2. Defining a maritime mission and a scenario in which lasercom systems are used.

3. Determining link performance requirements in terms of the signal-to-noise ratio and the bit-error rate, given a modulation technique and data requirements defined in Step 2.

4. Performing link budget calculations to determine the power received by a lasercom receiver, taking into account the transmitted power, gains, propagation losses, and implementation losses.

5. Determining the SNR using the results in Step 4.

6. Performing a parametric analysis to determine the lasercom system and operational parameters that meet the requirements derived in Step 3.

Furthermore, the ATP subsystems are assumed to perform “perfectly,” and errors attributed to the platform dynamics are neglected.

D. BENEFITS OF RESEARCH

Lasercom system designers can benefit from this research as it provides information for system design trade-offs vis-à-vis operational environment and operating range. Commanders involved in naval operations and mission planning which utilize lasercom can use the outcomes of this research to gain understanding of their operational boundaries and limitations and to make use of them towards increasing the lasercom system effectiveness and probability of mission success.

E. THESIS STRUCTURE

This thesis is divided into seven chapters. The first chapter provides background information about the research topics and highlights the benefits of the research. The second chapter provides information on lasercom and introduces the various elements of a lasercom system. The third chapter provides an overview of the maritime environmental conditions that would affect the link performance. The fourth chapter explains the bit-error rate and explains the parameters of the link budget. The fifth chapter provides an example of a link budget calculation and discusses the salient outcomes of the link budget analysis. Finally, the last chapter summarizes the thesis and underlines the key discussion points.

II. REVIEW OF LASER COMMUNICATIONS

This chapter focuses on the comparison between laser and RF communications, highlighting their advantages and disadvantages. In addition, this chapter also introduces the basic building blocks of a lasercom system and its basic operations.

A. ADVANTAGES OF LASERCOM OVER RF COMMUNICATIONS

The transferring of data from point A to point B through free space by optical means is known as free space optical communications (FSOC). FSOC presents an excellent mode of data transmission when laying cables between transmission systems is infeasible or when the FSOC system is mounted on moving platforms. The introduction of FSOC has generated great interest in both military and commercial applications because FSOC has the following advantages over the conventional RF communications (Majumdar 2008).

First, laser communications allow data rates of gigabits per second (Gbps), whereas RF communications offer data rates of megabits per second (Mbps). The communication data rate is proportional to the bandwidth (BW) of the carrier. The carrier is a waveform that is modulated by the input signal, and this carrier is also of a higher frequency as compared to the input signal. As the BW is a fixed fraction of the carrier frequency, a higher frequency results in an increase in the BW and, thus, speeds up transmission (Majumdar 2008). Commercially available lasercom systems offer capacities in the range of 100 Mbps to 2.5 Gbps. For example, the MRV TereScope® fixed wireless system, TS-10GE, shown in Figure 1, can provide data transfer up to a distance of 6.7 km and with data rate of 10 Gbps using the 1550 nm laser (MRV 2011). The TS-10GE is a dual aperture system with one aperture for transmission and the other for reception. An aperture is an opening that allows light to pass through.

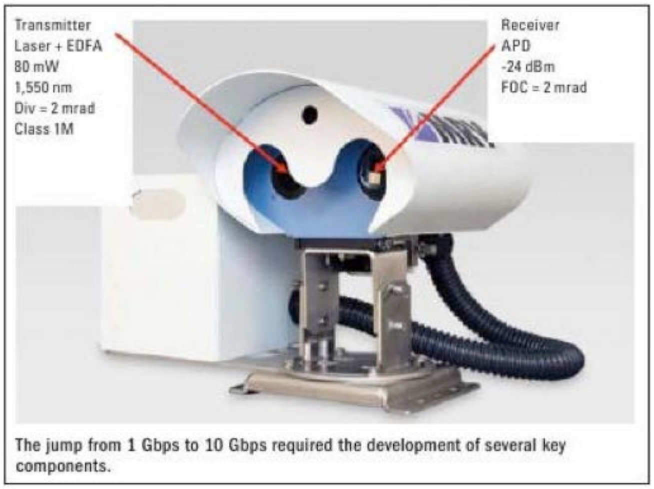

Figure 1. MRV's TS-10GE FSO (From MRV 2011)

Second, the FSOC's operating spectrum can be operated license-free. Currently, there is no requirement to register the frequency bands used above three terahertz (THz) and pay for the utilization of the BW. Being able to use the spectrum license-free would result in considerable time and cost savings in operating an FSOC system. However, the International Telecommunication Union (ITU) has begun its studies on the frequency bands above three THz, and frequency bands above three THz is considered as the beginning of the optical spectrum in which FSOC operates. Licensing for the frequency spectrum above three THz might be required in the future (International Amateur Radio Union 2011) and would drive up operation cost.

Third, laser has narrow beamwidth and, as a result, does not cause interference and thus allows frequency reuse. Interference refers to the interaction between two signals forming a resultant signal with characteristics different from the original signals. FSOC can, therefore, be regarded as having enormous amount of BW capable of delivering high data rates, as the data rate is equivalent to two times the available BW for bi-level encoding (Sklar 2001). As the beam is highly directional, laser communications do not have any issue of multipath effects observed in RF communications. Multipath refers to transmitted signals reaching the receiver by two or more paths.

Fourth, an FSOC system is relatively smaller and lighter and consumes lesser power as compared to its RF counterpart. As a result, considerable cost saving is incurred when operating an FSOC system (Leitgeb et al. 2009).

Fifth, narrow beamwidth, high directionality, and shorter time required for transmission by an FSOC system would also mean the FSOC system has the inherent capability of low probability of detect (LPD) and low probability of intercept (LPI) and makes it harder for adversary to implement jamming techniques. Consequently, FSOC enjoys higher security and interference immunity on the transferred data (Li 2003).

Sixth, when an FSOC system is integrated into an operational platform, there is little or no issue with regards to electromagnetic interference (EMI)/electromagnetic compatibility (EMC) as well as hazards of electromagnetic radiation to ordnance (HERO) requirements. The highly directional beam eliminates the need to provide extremely robust electromagnetic shielding to surrounding vulnerable electronics or ordnance systems, thereby reducing the cost of systems acquisition.

The FSOC also has its disadvantages and challenges. The main impediment to the widespread use of FSOC systems is the stringent alignment requirement and the degradation in their performance caused by adverse weather conditions.

B. ADVANTAGES OF RF COMMUNICATIONS OVER LASERCOM

RF communication systems have a few advantages over lasercom systems. First, the risk of using RF communications is inherently lower as RF technology and existing infrastructure are mature.

Second, as lasercom frequencies are much higher than those of RF communications, lasercom could suffer from severe power loss caused by atmospheric absorption, scattering, and turbulence.

Third, as RF communication systems have wider beamwidth, they do not require highly precise pointing for communicating. Laser beamwidth is in the microradian region while RF beamwidth is the milliradian region. The design and fabrication of an ATP system associated with lasercom is challenging, given the narrow beamwidth of the laser and the need to remove jitters introduced by both the external and local environments that alter the precision alignment of the ATP system. The typical beamwith is in the range of a few microradians, and the pointing accuracy has to ensure that the jitters produced are reduced to a fraction of the few microradians. Finally, highly unpredictable operating conditions such as frequent platform traffic could obstruct transmitting and receiving lasercom systems.

Toyoshima (2007) compares the performance of RF communications and lasercom systems for long-distance communication applications. As shown in Figure 2, three systems are compared. The first system is a lasercom system operating at 0.8 μm using intensity modulation and direct detection with an avalanche photodiode. Intensity modulation involves varying the magnitude of the optical output by a modulating signal. Direct detection requires only the intensity, and not the phase information, of the input signal to produce desired output signal (Hranilovic 2003). The second system is a lasercom system operating at 1.5 μm using on-off keying and an optical preamplifier. On-off keying is a form of amplitude modulation in which the carrier signal from a source is turned on and off to represent bit ‘1’ and bit ‘0’, respectively (Sklar 2001). The last system is an RF communications system operating in the X-band. At 10^4 km, both the 0.8-μm and 1.5-μm optical links have a higher signal-to-noise ratio (SNR) as compared to RF link. However, at approximately 10^8 km, the SNR for the optical links is much smaller than the SNR for the RF link. The SNR is the ratio between the received signal power and the noise power. A higher SNR would result in a better received signal quality. The SNR for a lasercom system is proportional to R^{-4} while the SNR for a RF communication system is proportional to R^{-2}, where R denotes the distance between the transmitter and the receiver. Furthermore, the maximum data rate of RF communications is higher than that of lasercom for the distance R beyond 10^8 km. The plot on the right in Figure 2 shows that the maximum data rate for the RF link is higher than that for the optical links at a distance greater than 10^8 km. It is, thus, more effective to use lasercom for communications for distances less than 10^8 km and RF communications for distance beyond 10^8 km.

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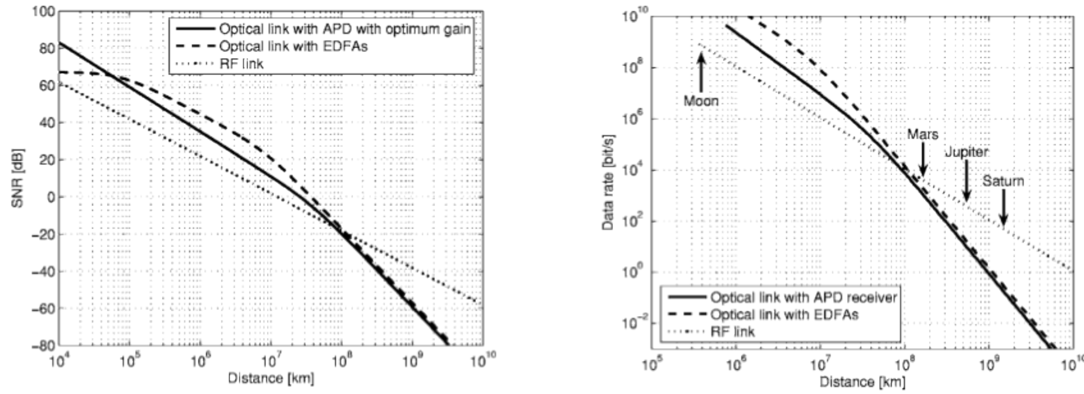

Figure 2. *SNR* (left) and maximum data rate (right) comparison between lasercom and RF communication systems (From Toyoshima, 2007)

As discussed above, both lasercom and RF systems have their advantages and disadvantages. The decision to employ a system of either technology (RF or laser) depends on the applications/needs of the system, the environmental conditions in which the system is employed, the maturity of the technology, and users' willingness to accept risks.

C. FREE SPACE OPTICAL COMMUNICATION SYSTEM (FSOC)

The previous section discusses the advantages and disadvantages of using lasercom for wireless communications. Similar to those of an RF communication system, the basic components of an FSOC system perform generation, modulation, transmission, reception, and processing of signals. The basic building blocks of an FSOC system described in (Li 2009), as shown in Figure 3, are the laser, modulator, signal source, spectroscope, APT system, optical emitting antenna, filter, optical receiving antenna, photoelectricity detector, and systems for disposal of information and export of incept information. The transmitting section of the FSOC system consists of the laser, signal source, modulator, spectroscope and optical emitting antenna. The receiving section comprises the optical receiving antenna, photoelectricity detector, filter and spectroscope.

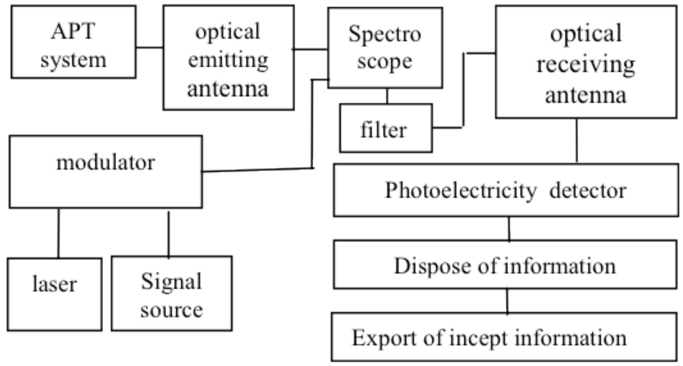

Figure 3. FSOC system (From Li, 2009)

The transmit operation requires the conversion of the data signal from the signal source to an electrical signal by modulating the laser beam. Having passed through the spectroscope for spectrum selectivity, the modulated signal (laser beam as the carrier) is then transmitted via the optical emitting antenna. The output optical power produced must be adequate to overcome the attenuation it would encounter before reaching the receiver. The receive operation entails the reception of the modulated signal into the photoelectric detector in which the electric signal is reverted to the original signal via a converter. Adequate receiving antenna gain and sensitivity are required to ensure that the signal received can be reverted to the original data signal.

Besides the transmitting and receiving sections, the ATP system is also of immense importance. Laser communications are established based on highly precise line-of-sight (LOS) pointing. To achieve the exact pointing direction, the transmitter must be able to locate and acquire a pointing reference onto the receiver. The pointing reference refers to a point or an area on the receiver on which the light beam impinges. The acquisition of the pointing reference to the receiver/transmitter must then be followed by the tracking of the acquired pointing reference in order to ensure that both ATP systems still point to each other throughout the communication process. Effective communications require precise positioning and pointing of the transmitting and receiving platforms. The stability of the platform must thus be maintained and disturbances caused by the environment as well as the random motions of both the communicating platforms be minimized.

1. Transmitter

One of the most fundamental units of the FSOC system is the laser transmitter, which produces the laser beam to be modulated and transmitted through free space. The commonly used laser types are the gas laser, dye laser and solid-state laser. Figure 4 shows the examples of each laser type and their corresponding lasing medium. The lasing medium is also known as the active laser medium producing the optical gain for laser. An electric current or optical source is directed or impinged on the lasing medium to create coherent light. Gas laser is produced by passing an electric current through a gas, typically, helium-neon (HeNe), carbon dioxide (CO_2), and argon (Ar), to produce a coherent light. The dye laser is produced by directing a high-energy source of light into an organic dye mixed with a solvent. The dye laser is able to operate with a wide range of emission wavelengths from ultraviolet to the near-infrared region (0.2 to 1.2 μm) by using different dyes. Typical dyes used for dye laser are fluorescein ($C_{20}H_{12}O_5$), coumarin ($C_9H_6O_2$) and umbelliferone ($C_9H_6O_3$). Common forms of solid-state laser include semiconductor laser, ruby laser, and Nd:host laser (such as Nd:YAG (neodymium-doped yttrium aluminium garnet) or Nd:Glass) (Boone 2004). For lasercom systems, solid-state optical transmitters are widely used. A detailed discussion of light emitting diodes (LEDs) and laser diodes follows.

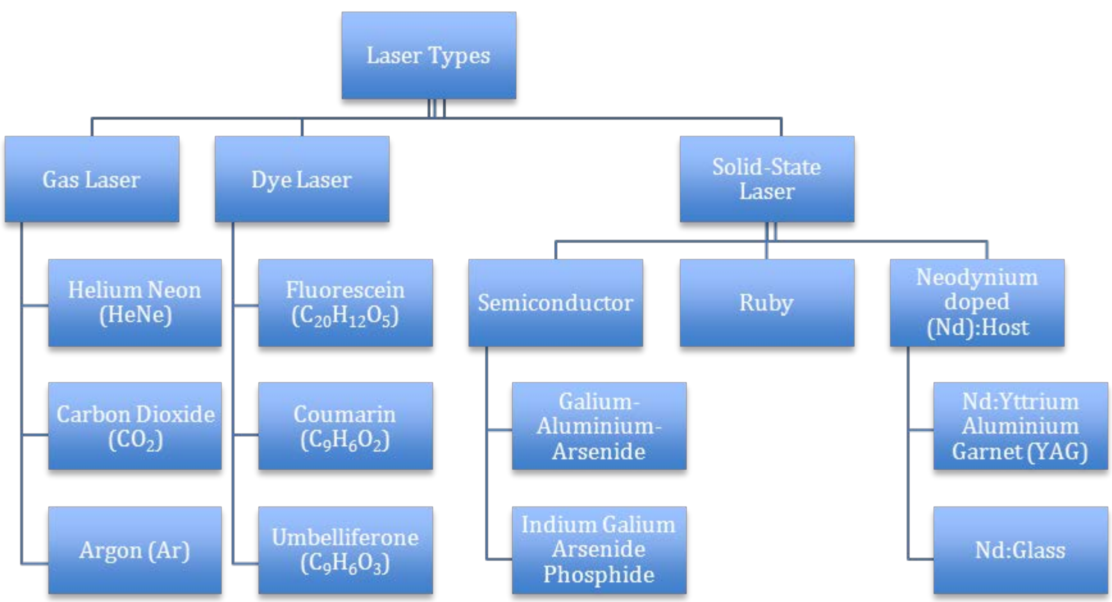

Figure 4. Common laser types (After Nelson, 2004)

Both LEDs and laser diodes have the same basic physical structure and energy diagram. The energy diagram depicts the energy levels of the electrons in an atom or molecule. An electron can move up from an energy level to a higher energy level by absorbing energy from an incident photon or descend to a lower energy level by emitting a photon. The main difference between an LED and a laser diode is that the LED produces incoherent light while a laser diode produces coherent light. Coherent light like laser contains only a single wavelength with same phase, whereas incoherent light contains more than one wavelength with varied phases. An LED can result from simply fusing a N-type material with a P-type material. Most semiconductor materials are poor electrical conductors. An N-type material refers to the doping of impurities, known as donors, into the semiconductor materials. Donors are the elements from Group V of the Periodic Table of the Elements. When introduced into the intrinsic semiconductor material, each donor atom would replace a semiconductor atom, thereby adding a free electron and making the semiconductor material more conductive. Similarly, for a P-type material, acceptors from Group III elements are added to the intrinsic semiconductor material to provide additional free holes and, thereby, increase its conductivity. A diode is formed when the N-type material and the P-type material are brought together and sandwiched between two electrodes. The bonding of the N-type material and the P-type material results in the combining of the free electrons and holes, leading to the formation of the depletion zone when no voltage is applied. The depletion zone consists only of ionized donors or acceptors as all the free electrons and holes are expelled from the zone. By providing a forward bias above a threshold, i.e., connecting the N-type side electrode to the negative potential and the P-type side electrode to the positive potential, the electrons and holes are free to move again and combine. When they combine, the energy of the photons, E_p, is released, and light is emitted spontaneously with a wavelength $\lambda = hc / E_p$, where h is the Planck's constant and c is the velocity of light in vacuum (Gupta 2005).

The difference between a LED and a laser diode is the stimulated emission of photons that results in the coherency and directionality of the laser light. To produce laser light, there is a need to have an external light source of a specific wavelength to excite the lasing medium atoms so as to produce a large amount of highly energetic electrons. When the energized electrons recombine with holes, they produce photons of a specific wavelength. These photons can induce emission from other atoms that possess electrons in the same excited state resulting in simulated emission. A cascading effect occurs releasing light of the same frequency and direction. The above operation is usually completed with the additional pair of mirrors at the end of the lasing medium forming a resonant cavity. These released photons are reflected to and fro between the mirrors to simulate more emission of the same wavelength and phase. One of the mirrors allows some photons to flow through while reflecting the rest of the photons. The photons that get through the mirror form the laser light (Gupta 2005).

The laser transmitter type to be used depends on the detection method, which is categorized under coherent detection and direct/non-coherent detection. For coherent detection systems, both the intensity and the phase information are extracted from the transmitted signal while, for direct detection systems, only the intensity of the laser beam is of importance. In coherent detection systems, the optical signal received is mixed with a light signal generated from a local oscillator laser (LO-laser). The combined signals are then impinged onto the detector to generate an electrical signal that contains the transmitted data. In direct detection systems, the receiver only requires to have an input signal energy that is high enough to distinguish between an output signal and detector output noise. The advantages of coherent detection include better sensitivity and less susceptible to background light. If the input light signal were perfectly mixed with the signal generated by the LO-laser, the system could be immune to background light and able to obtain a desired error probability for low intensity signals. The requirements for the transmitter of a coherent optical system are shown in Table 1 (Pribil 2009).

Table 1. Requirements of a coherent system transmitter (After Pribil, 2009)

Requirements	Description
Single frequency operation	The transmitter works like an oscillator, and it is necessary that there is only one frequency such that all energy can be concentrated at this frequency. This implies that there can only be one mode in which all the energy is contained. By having more than one mode, the signal power would be spread out and result in lower power of the signal of interest.
Modulation BW	Sufficient transmission BW should be catered to ensure that the communication channel is able to support the data rate. A dedicated modulator is used for high data rate requirement.
Optical output power	There should be enough power catered based on link budget computation and extra margin to compensate for component degradation and weather disturbances.
Stable operation	Component selections are critical to ensuring they perform consistently under all operating conditions. The optical output is critical as a dip in power could lead to data error and a frequency drift would lead to communication breakdown.
Low phase noise	LO-laser phase noise should be kept as low as possible for high-sensitivity operations in which the input signal is low.
Stable polarization	The polarization of the transmitted signal should be maintained so as to prevent loss of signal at the receiver end.

2. Modulator

The modulator encodes the information to be transmitted into the laser light. Depending on the modulation techniques/schemes used, the laser light is being modulated by varying its intensity, frequency, phase or polarization by the data signal. In analog modulation, the modulation to the laser light is continuously being applied which corresponds to the analog information signal. In digital modulation, the laser light is being modulated by discrete signals. The modulation can be done directly by the light source itself or indirectly by using an external modulator. For direct modulation, the digital signal can be easily manipulated to turn on and off the laser source to create a pulsed laser beam. However, on-and-off turning of the laser diode can cause thermal and electrical stress, which would degrade the life of the laser diode and cause the frequency of the laser to shift. For indirect modulation, the continuous light from the light source is modulated by an external modulator. This approach eliminates the problem in direct modulation; however, the circuit would be more complex. Another advantage of external modulator would be operation speed as the limiting factor for direct modulation to achieve high-speed operation is frequency chirping. Frequency chirping refers to changes in signal frequency.

There are two main types of external modulator: Mach-Zehnder interfernometer (MZI) and electro-absorption (EA) modulator. The MZI modulator utilizes the effect of refractive index change to a crystal medium when an electric field is applied to the medium. The EA modulator utilizes the effect of changing the absorption coefficient of a semiconductor material medium when an electric field is applied to the medium. As shown in Figure 5, the Y-junction on one end of the MZI modulator splits an incoming laser beam into two coherent beams, which are combined at the Y-junction at the other end. A phase modulation could take place in either one or both of the split paths. The modulating signal causes the optical path of the two beams to be different, and, when combined, they merge constructively or destructively, thereby varying the amplitude of the output light. Biasing is required to establish an operating point so as to ensure that the amplitudes of the split beams are symmetric. Symmetry in amplitudes of the split beams means that the amplitudes of the split beams are the same and, if 180° out of phase, the resultant output would be zero. An EA modulator makes use of the property of transmissivity of the semiconductor material to create on-off switching. It has the same structure as the laser diode, and the transmissivity of the semiconductor medium is changed by applying a reverse bias. Table 2 shows a general comparison between the MZI modulator and the EA modulator. The greatest advantage of the EA modulator over the MZI modulator is the EA modulator's ability to monolithically integrate with the laser as the EA modulator's structure is similar to the laser's. As a result, production cost is reduced and insertion loss and alignment issues are eliminated. The EA modulator also requires lower driving voltage as compared to the MZI modulator during operation, thereby requiring less power. On the other hand, the MZI is better than the EA modulator as the MZI modulator can be implemented with no frequency chirping. The MZI modulator also has a better extinction ratio and BW capability. The extinction coefficient is a ratio between the average power level for logic "1" and the average power level for logic "0." A high extinction ratio is desired as it is associated with a higher gain for the modulator, and higher BW implies higher operation speed (Brillant 2008).

Table 2. General comparison between the MZI and EA modulator (From Brillant, 2008)

Modulator parameter	**MZI**	**EA**
Monolithic integration with laser	No	Yes
Driving voltage	Higher	Lower
Chirping	Can be eliminated	Cannot be eliminated
Extinction ratio	Higher	Lower
BW	Can be higher	Slightly lower
Heating	Less problematic	More problematic

The Naval Research Laboratory has been working on the modulating retro-reflector (MRR); the MRR is made by mounting an electro-optic shutter in front of a retro-reflector. The MRR is primarily developed for smaller platforms such as unmanned aerial vehicles (UAV), which are limited in space, weight, and power. The MRR is lightweight and transfers all the power requirements to a larger platform with which it is communicating. Figure 6 shows the operation of the MRR. The larger platform sends an interrogation beam (unmodulated laser beam) to the MRR and a modulated laserbeam, via the operation of the electro-optic shutter, would be passively reflected back to the larger platform. The modulation is performed by turning on and off the electro-optic shutter with an electrical signal that corresponds to the data to be transmitted from the UAV (Naval Research Laboratory 2010).

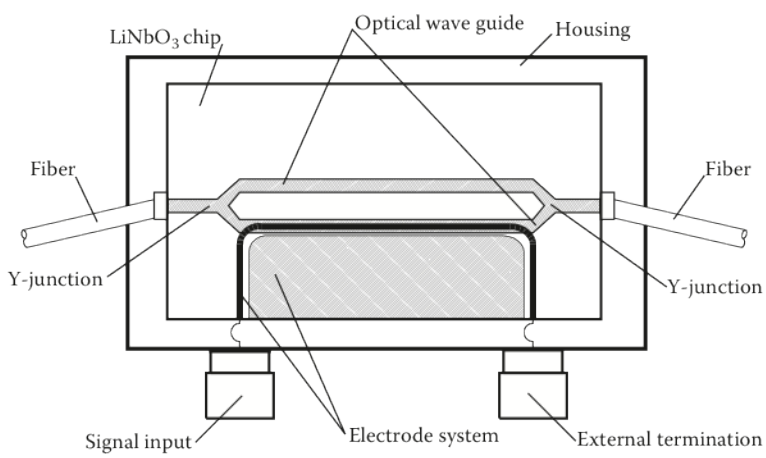

Figure 5. Functional diagram of an optical modulator (From Pribil 2009)

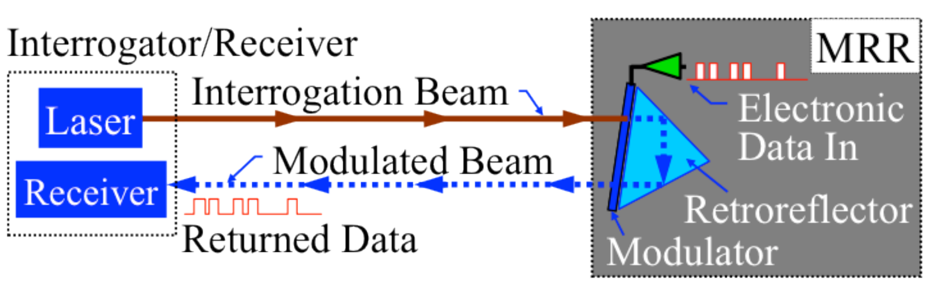

Figure 6. Operation of MRR (From Naval Research Laboratory 2010)

3. Receiver

The received signal passes through a filter to have the background noise removed before reaching the optical detector. The optical detector converts the power in the received signal into an electrical signal. This electrical signal is then amplified and sent for signal processing to retrieve the original information. Optical detectors are largely categorized into photon detectors and thermal detectors. In order for a photon detector to respond, the energy of the photons must be high enough to interact with the semiconductor material atoms to generate free electrons to increase the conductivity of the material. The response of the optical detector is highly dependent on the wavelength of the generated photons.

Photon detectors can be grouped according to the mechanism that produces a response. They are photoemissive (PE), photoconductive (PC), and photovoltaic (PV). PE detectors are governed by the photoelectric mechanism, whereby charge carriers are produced proportionately with the incident photons. In PC detectors, free electrons released by the incident photons change the conductivity of the detector material proportionate to the intensity of the light. In PV detectors, the change in voltage is proportionate to the incident radiation (Paschotta 2010). Photon detectors, such as photodiode detectors, are widely used for optical communications, because they have fast responses, high sensitivity, and high quantum efficiency. When photons of energy higher than the energy gap fall on the photodiodes, electron-hole pairs are generated, resulting in a current flowing through an electrical circuit.

Table 3. Semiconductor materials and their effective spectral range (After Seeger 2004)

Material	E_g **(eV)**	λ_c **(nm)**	**Spectral range (nm)**
Si	1.12	1100	500 – 900
Ge	0.67	1850	900 – 1300
GaAs	1.43	870	750 – 850

InGaAsP	0.38 – 2.25	550 – 3260	1000 – 1600

Table 4. Important parameters of an optical detector (After Pribil 2009)

Parameter	Description
Responsivity	Defined as the detector output per unit input power. Its units are amperes/watts (A/W) or volts/watts (V/W), depending on whether the output is current or voltage.
Noise Equivalent Power (NEP)	Defined as the incident optical power that produces a signal voltage (or current) equal to the noise voltage (or current) of the detector. Its unit is watts (W). The lower NEP is, the better is the detector at detecting weak signals.
Detectivity (D*)	Defined as the square root of the detector area per unit value of NEP. It is wavelength-, frequency-, and BW-dependent and its unit is centimeters-(hertz)$^{1/2}$/watts (cm-Hz$^{1/2}$/W). The higher D* is, the better is the detector at detecting weak signal.
Quantum Efficiency (Q)	Defined as the ratio of electron-hole pairs generated to the number of incident photons. The higher Q is, the better is the detector at detecting weak signals.
Detector Response Time	Defined as the duration during which the detector responds to changes in light intensity. Its unit is seconds. The rise and fall/decay times are usually associated with the response time. The rise time is defined as the time taken for the output to rise from 10% to 90%. The fall time is defined as the time taken for the output to fall from 90% to 10%.
Spectral Response	Defined as the variation in the performance of the detector when the wavelength changes. It is important to take note of the spectral region to which the detector responds well when designing applications.
Linearity	Indicates whether the output is linear with the input intensity. The slope that characterizes the output with respect to the input of the detector should not vary. Saturation can occur when the detector is not used within a specified light level. Saturation results in output level that could no longer be used to represent the input to the detector effectively.

The energy gap, E_g, is located between the conduction and valence bands in semiconductors (e.g., E_g = 1.12 eV for Silicon and E_g = 0.67 eV for Germanium). The electron orbits of the atoms, when brought closer together, overlap, and the discreet energy levels of the free atoms become these bands. The maximum wavelength, also known as the cutoff wavelength, λ_c, that can be detected by the detector is given by

$\lambda_c = h_c / E_g$. Table 3 lists some semiconductor materials for the detector and their respective spectral range (Seeger 2004).

There are three types of photodiodes: p-type material- n-type material (PN) photodiodes, p-type material- insulator- n-type material (PIN) photodiodes, and avalanche photodiodes. Avalanche photodiodes are the choice detector because they are more sensitive than the other two photodiodes, in the sense that internal gain within the photodiode increases the effective responsivity of the device. The internal gain results from each photo-generated carrier being multiplied by avalanche breakdown, allowed by much higher reverse bias maintained by temperature compensation circuits (Nair 2009).

Several characteristics are used to determine the performance of optical detectors. Table 4 shows the list of important parameters of an optical detector.

4. Acquisition, Tracking, and Pointing System

The basic block diagram of an ATP system is shown in Figure 7 (Liu 2011). The block diagram of the ATP system comprises five sections: the rough tracking detector and rough tracking controller section, the accurate tracking detector and accurate tracking controller section, the servo system section, the double-axis gimbal and the antenna array section. During the initial acquiring phase, the receiver from platform A, A_R, would scan for signal transmitted by platform, B, in a general direction and area based on estimated position of platform B and/or prior communications. The transmitted signal from platform B, B_T, during the acquiring phase is known as the beacon light. The task of capturing the beacon light is accomplished by the rough tracking detector, the rough tracking controller, the double-axis gimbal, and the servo system.

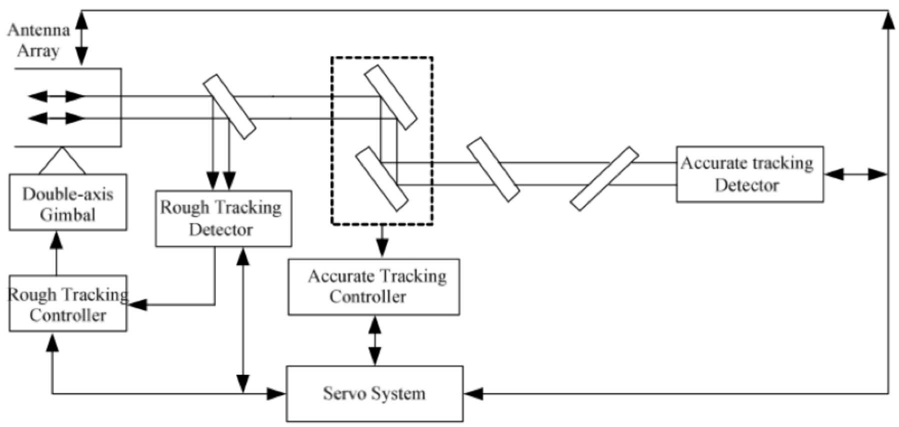

Figure 7. Block diagram of ATP system (From Liu 2011)

The rough tracking controller and detector would detect the approximate position of the beacon beam and provide feedback to the servo system which then moves the double-axis gimbal for antenna array position adjustment. The alignment of the beacon light to the center of the antenna array is essential for the transition from the detection phase to the tracking phase. During the tracking phase, the laser beamwidth of B_T would become narrower and data signals would start to be transmitted to platform A. The ATP system, aided by effective algorithms, must be able to provide sub-microradians pointing errors through the utilization of state-of-the-art components that could minimize noise and improve the dynamic range. The dynamic range refers to the range of the signal levels that a system is able to process and provide the desired output (Bensky, 2004).

a. Adaptive Optics

As discussed in detail in Chapter III, a laser beam experiences absorption, scattering, and turbulence as it propagates through the atmosphere. As a consequence, beam intensity degradation and wavefront aberrations occur, resulting in optical signal distortions and thereby adversely impacting laser communications. Adaptive optics, a scientific and engineering approach, can be used to overcome the distortions by analyzing them and modifying the optical signal shape (Tyson 1998). Adaptive optics may thus be a necessary part of the ATP system of a lasercom system.

Figure 8 shows a generic block diagram of an adaptive optic imaging system. The basic building blocks of the system are the beam splitter, wavefront sensor, adaptive mirror, imaging detector, and a control computer to perform real-time computation required for the modifications of the laser beams wavefront.

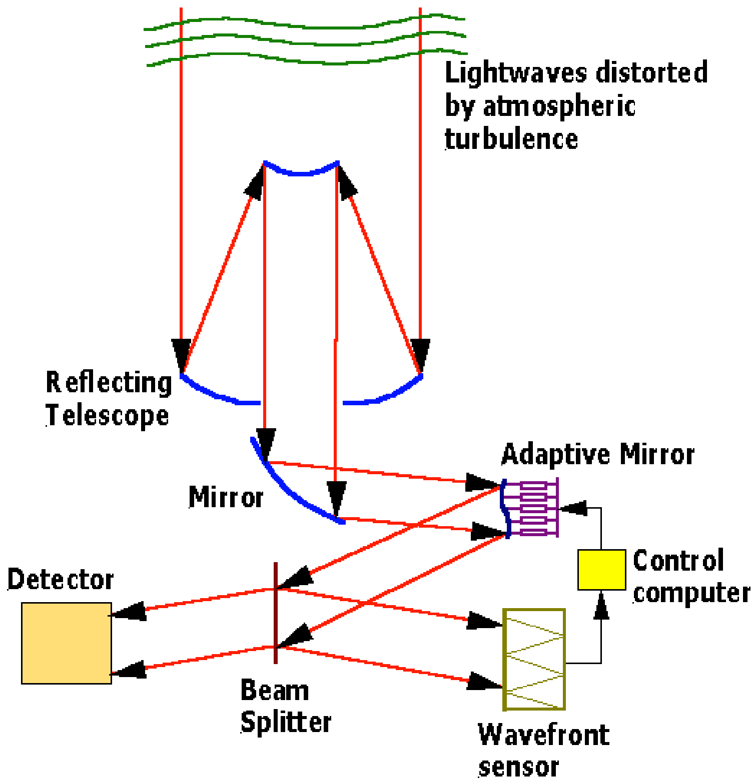

Figure 8. Adaptive optics imaging system (From Emery 2002)

The function of the adaptive mirror is to provide the wavefront modification to the laser beam. The beam splitter splits up a single beam into two, preferably without distorting the phase of the beams, such that the replicated beams are of high fidelity. The most common detector is the charged-coupled device (CCD) array. Wavefront sensing is highly sensitive to noise. The CCD has low noise because of its low loss clocking process and, therefore, is an ideal selection as the detector. The wavefront sensor samples the incoming beam and provides data to the control computer, which computes the required modifications to the optical path. Thereafter, the control computer provides signals through a series of high-speed actuators within the adaptive mirror in which the modifications would be implemented. For an ideal wavefront, the wavefront should be flat and would produce a known pattern for reference. For an aberrated wavefront, there would be offset in the pattern produced. During the process of rectifying the distorted images, the system compares the beam from the target to the reference beam repeatedly. This repeated process enables the adaptive optics imaging system to track the rapid changes of the beam's wavefront caused by atmospheric turbulence and make the necessary alterations to rectify the aberrated wavefront.

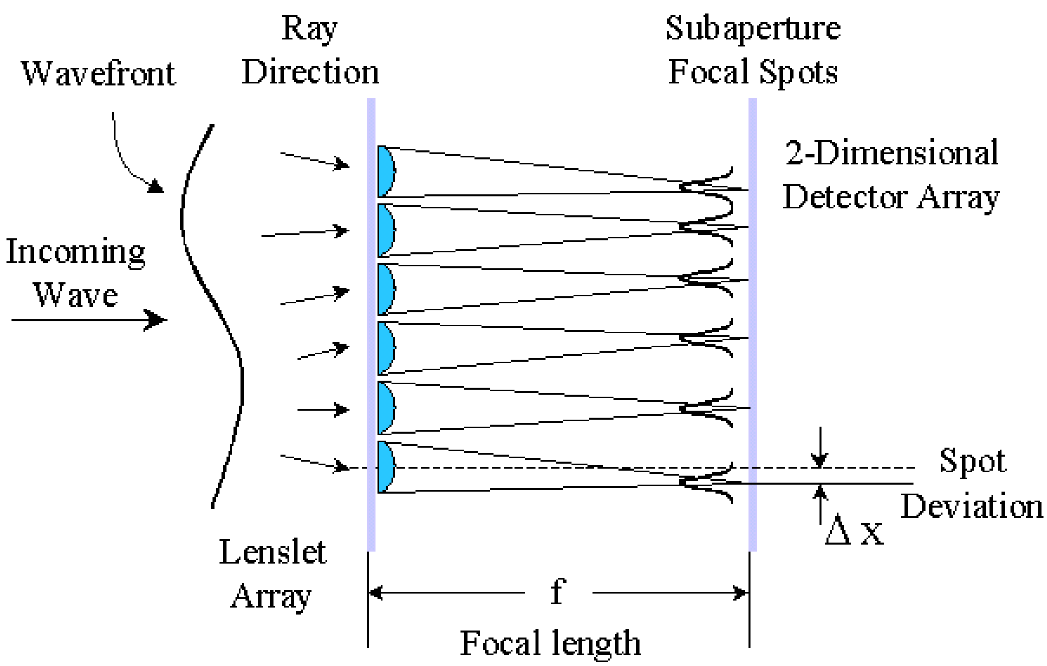

Figure 9. Shack-Hartmann wavefront sensor using a lenslet array (From Seo 2001)

Figure 9 shows the Shack-Hartmann wavefront sensor using a lenslet array for wavefront correction. The laser beam is divided into spot images onto the two-dimensional detector array of the wavefront sensor. The offset produced due to turbulence can be related to the local slopes of the wavefront at each of these lenslets. The lenslets collected the slope information from the beam and transmit it to the control computer for processing. The direct method to perform wavefront corrections is to control the actuators within the adaptive mirror by using the wavefront slope information. A calibrated voltage is applied from the control computer to the actuators to achieve the required deformation to the adaptive mirror to correct the wavefront slope error. The aim of the correction process is to achieve the desired deflection of the adaptive mirror to reduce the slope error to zero so as to achieve a flat wavefront (Corley 2010).

b. *Isolation, Feed-Forward, and Feedback Mechanisms to Minimize Local Disturbance*

The platform, which the ATP system is mounted on, generates disturbances such as rotational and translational random movements and vibrations to the ATP system. The disturbances are commonly depicted by power spectral density (PSD) plots, such as those shown in Figure 10. The sudden and random movement of the platform limits the ability of the ATP system to maintain precise pointing for communications with the other platform. An isolation and/or feedback system is necessary to be incorporated into the ATP system. The isolation and feedback mechanisms reduce the effects of the disturbances caused by the platform. Figure 10 shows the effects of implementing the various isolation and feedback mechanisms on the platform disturbances (Hemmati 2008).

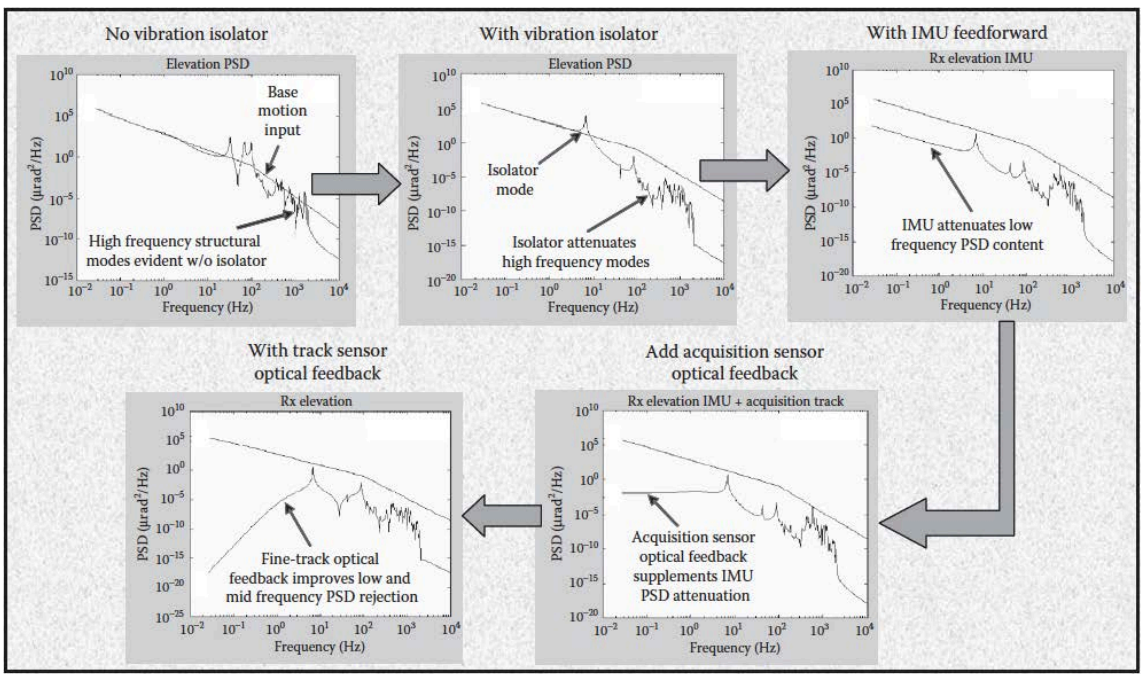

Figure 10. Effects of implementing the various isolation and feedback mechanisms on the platform disturbances (From Hemmati 2009)

The first plot ("No vibration isolator") of Figure 10 depicts the high-frequency disturbances introduced by the platform (base) motion when no isolation system is implemented. The second plot ("With vibration isolator") shows that the high-frequency disturbances are attenuated with the vibration isolator implemented. The third plot ("With IMU feedforward") shows that with the implementation of an inertia measurement unit (IMU), providing feed-forward information to the ATP system, the low-frequency disturbances are reduced. The IMU is an electronic device that measures a platform's relative position, velocity, acceleration and orientation using gyroscopes and accelerometers on the platform in motion (Siciliano 2008). By implementing both the vibration isolator and IMU feed-forward systems, the high- and low- frequency disturbances could be reduced. The fourth plot ("With track sensor optical feedback") illustrates that the low-frequency disturbances would be further reduced with the addition of an optical feedback during the acquisition phase. The final plot ("Add acquisition sensor optical feedback") shows that the low- and mid- frequency disturbances would be further reduced with the addition of an optical feedback during the tracking phase.

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III. EFFECTS OF MARITIME ENVIRONMENTAL CONDITIONS ON LASER COMMUNICATIONS

A laser beam loses its power as as it propagates in a maritime environment. The power losses are called atmospheric losses. As shown in Figure 11, the causes of the atmospheric losses are atmospheric absorption, MIE scattering, and turbulence-related phenomena such as scintillation, beam wander, beam spreading and wavefront aberration (Tyson 1998). The determination of the lasercom link budget takes into account the atmospheric losses experienced by the laser beam travelling from a transmitter to a receiver. This chapter explains the causes of the atmospheric losses, describes the link budget calculation, and discusses ways to improve the received laser power.

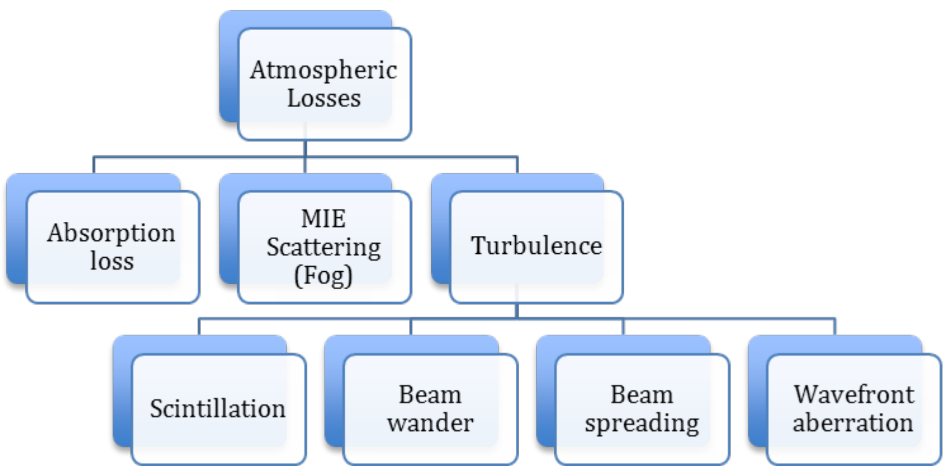

Figure 11. Atmospheric effects

A. ABSORPTION LOSS

An electromagnetic wave propagating in a medium experiences energy loss as part of the signal energy is converted to other forms of energy. For example, as electromagnetic waves (e.g., light waves) propagate in the atmosphere, some or all of the energy contained in the waves are absorbed by the atmosphere and converted into heat, resulting in attenuation of the light wave energy (Weik 1997). The molecules in the atmosphere that contribute to absorption are the oxygen (O_2), nitrogen (N_2), carbon dioxide (CO_2), argon (Ar), methane (CH_4), nitrous oxide (N_2O), carbon monoxide (CO), water vapor (H_2O), and ozone (O_3). The top five graphs in Figure 12 show the absorptance of the various gas molecules (except Ar), and the last graph shows the combined absorptance. Absorptance of a medium refers to its ability to absorb the electromagnetic wave energy per unit time as the wave propagates in the medium (Weik 1997).

Ultraviolet (UV) light below 0.3 μm is highly attenuated by O_2 and O_3, and visible light (0.4 to 0.7 μm) is only slightly attenuated by O_2 and O_3. The near infrared region (0.7 to 1.5 μm), which is commonly used for lasercom, is absorbed by several H_2O bands. The rest of the infrared region (mid and far infrared, between 1.5 to 1000 μm) is absorbed by most of the gases, with H_2O and CO_2 being the two more dominant gases.

Figure 13 is based on MODTRAN simulation of the atmospheric transmittance over a horizontal path of 10 km at sea level with wavelengths between 400 and 2500 nm. MODTRAN is an atmospheric radiative transfer model developed by Spectral Sciences Inc. and the U.S. Air Force Research Laboratory (Spectral Sciences Inc. 2009). The visual range is 23 km; it refers to the maximum distance at which an observer can make out the outline of an object. According to the international visibility code, visual range of 23 km implies that the atmosphere is clear (refer to Table 5). Transmittance is the ratio between the electromagnetic wave energy that is transmitted through a medium and the electromagnetic wave energy that is incident on the medium (Academic Press, INC 1992). Figure 13 reveals that the transmittance spectrum consists of windows of high transmittance and zero transmittance (Hemmati 2009).

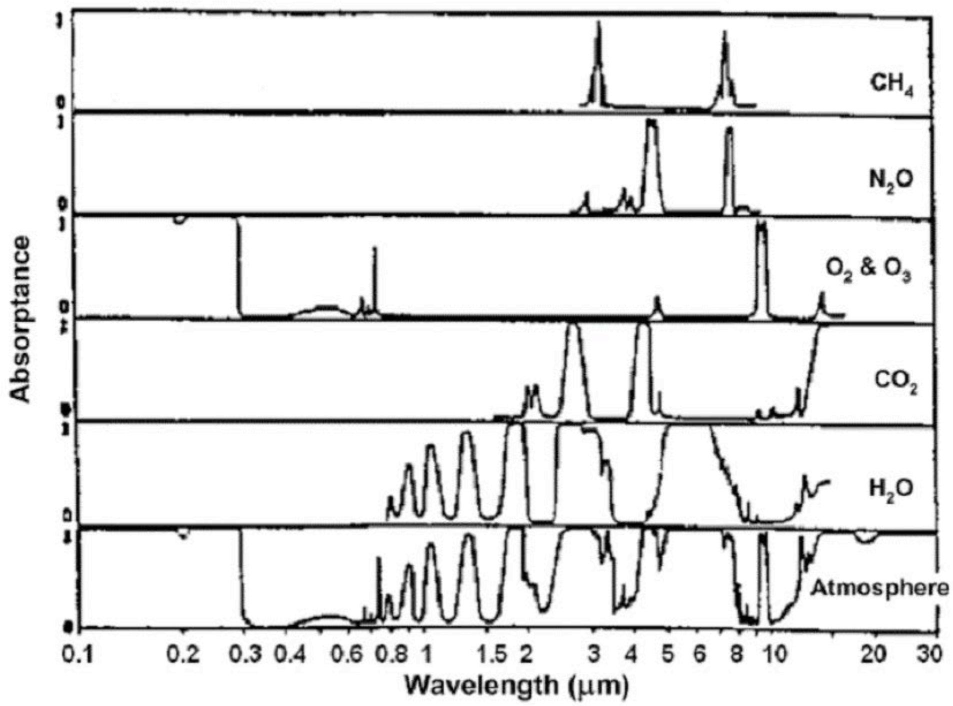

Figure 12. Atmospheric absorption of electromagnetic radiation by various gas molecules (From Fleagle 1980)

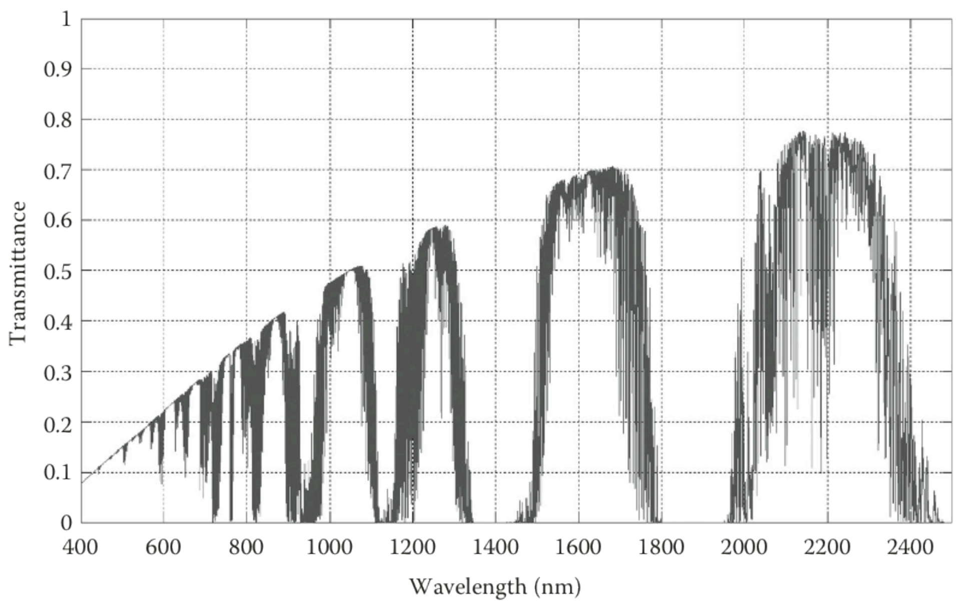

Figure 13. MODTRAN simulation-based atmospheric transmittance over 10 km at sea level. Clear sky with visual range of 23 km is assumed (From Hemmati 2009)

B. SCATTERING

Scattering is another phenomenon that causes electromagnetic wave attenuation. Electromagnetic waves such as light waves are reflected or scattered by tiny particles in the atmosphere (Hulst, 1981). There are two main types of scattering: Rayleigh scattering and Mie scattering.

Rayleigh scattering, also known as molecular scattering, is caused by sufficiently small, dielectric (non-absorbing), and spherical particles. Rayleigh scattering has a spectral dependence of λ^{-4}. This dependence means that light of longer wavelength (lower frequency) would experience less scattering as compared to light with shorter wavelength (higher frequency).

Mie scattering has a spectral dependence of approximately λ^{-1} and Mie scattering's presence is greatly felt in particle-rich air at visible and near infrared wavelengths (Sigrist, 1994). Aerosols are particles that linger in the air for an extended period of time; these particles can be of different sizes, shapes, distributions, constituents, and concentrations and can be found at all altitudes and at different geographic locations. Aerosols are generally created at the earth's surface and their concentration drops at higher altitude. As a result, the presence of aerosol particles in the atmosphere would have more pronounced scattering effects on light as compared to the atmosphere without aerosol particles.

Figure 14 shows a combined effect of Rayleigh scattering, Mie scattering, and water vapor on the atmospheric transmittance (Hemmati 2009) and the alternating low and high transmittance regions primarily caused by water vapor. Rayleigh scattering is negligible beyond 1200 nm, and Mie scattering exists throughout the entire spectrum with more pronounced effects at shorter wavelength. Lasercom operating in the near-infrared region is most affected by fog and clouds that have water droplets with sizes comparable to the laser wavelength. Table 5 shows the amount of light wave attenuation per kilometer of transmission at different fog levels (Fischer 2004).

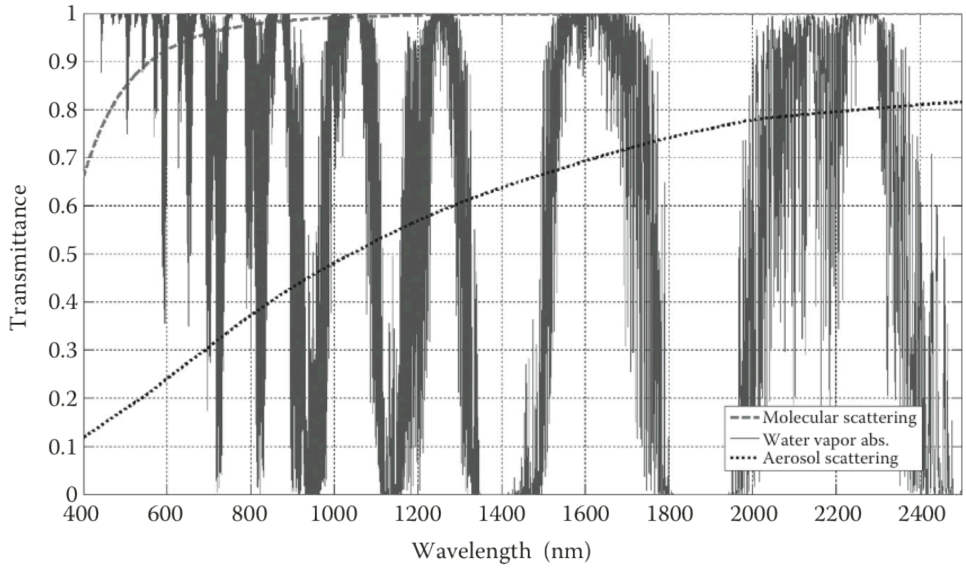

Figure 14. Contribution of Rayleigh scattering, Mie scattering, and water vapor to the atmospheric transmittance (From Hemmati 2009)

Table 5. Visual range conditions and attenuation based on the international visibility code (From Fischer 2004)

Description	Visual range	Loss (dB km^{-1})
Dense fog	40–70 m	250–143
Thick fog	70–250 m	143–40
Moderate fog	250–500 m	40–20
Light fog	500–1000 m	20–9.3
Thin fog	1–2 km	9.3–4.0
Haze	2–4 km	4.0–1.6
Light haze	4–10 km	1.6–0.5
Clear	10–25 km	0.5–0.1
Very clear	25–50 km	0.1–0.04
Extremely clear	50–150 km	0.04–0.005

Finally, as will be used in the link budget calculation, a semi-empirical equation, known as the Kruse equation, that relates the extinction of the optical signal to wavelength and the visual range is (Fischer 2004)

$$\Gamma(V;\lambda) = \frac{17}{V}\left(\frac{550}{\lambda}\right)^{0.585V^{1/3}} \tag{1}$$

where, V is the visual range in km, λ is the wavelength in nm, and Γ is the attenuation in dB per km.

C. TURBULENCE

Atmospheric turbulence is caused by the variation of the atmosphere's refractive index. When the sun heats up the earth's surface, hot air rises and cool air sinks. The mixing of the less dense, rising hot air and the more dense, cool air causes the atmosphere's temperature and density to vary randomly. As a result, the refractive index of the atmosphere fluctuates randomly. As light moves through regions with different refractive indices, some parts of the beam would be refracted, dispersed, or reflected. The most important effects caused by atmospheric turbulence on the propagation of light would be wavefront aberration, beam broadening, beam wander, and scintillation (Tyson 1998).

The severity of light wavefront aberration, beam broadening, beam wander and scintillation is closely related to the refractive index structure, C_n^2, which reflects the strength of the atmospheric turbulence. The larger C_n^2 is, the stronger is the turbulence. C_n^2 changes with time, altitude, and geographical location. C_n^2 would be lower at night and highest around noon. C_n^2 is dependent on the variation in air density. When the air density variation decreases, C_n^2 decreases. At high altitudes, where the air density variation is small, C_n^2 is small. Correspondingly, at low altitudes, nearer the earth's surface, C_n^2 is large because of large air density variation. Table 6 shows the C_n^2 profile at 3 m above the ground in New York during the months of February to May (Spencer

1978). Table 7 provides some estimation for the C_n^2 for a few scenarios. Data collected over water shown in Figure 15 indicates that turbulence decreases as the difference in the temperature between water and air decreases.

Table 6. Refractive index structure at 3m height above ground in New York (From Spencer 1978)

		LOG C_n^2 STATISTICS (TYPE I)		LOG C_n^2 STATISTICS (ALL WEATHER)	
		MEAN	STD. DEV.	MEAN	STD. DEV.
FEB	NIGHT	-14.13	0.58	-14.12	0.68
	DAY	-12.76	0.41	-13.63	0.76
MAR	NIGHT	-14.33	0.60	-14.05	0.75
	DAY	-12.70	0.52	-13.12	0.82
APR	NIGHT	-13.67	0.43	-13.64	0.51
	DAY	-12.79	0.62	-12.82	0.63
MAY	NIGHT	-13.49	0.54	-13.54	0.57
	DAY	-12.56	0.37	-12.85	0.63

TYPE I: CLEAR SKY; FAIR WEATHER

Table 7. Refractive index structure estimation for different scenarios (After Harney 2005)

		Refractive Index Structure C_n^2 (3m) ($m^{-2/3}$)	**Refractive Index Structure** C_n^2 (h) ($m^{-2/3}$) (h ≤ 100 m)
Day	Any Terrain, Clear Weather	10^{-13}	C_n^2 (3 m) $(h/3)^{-4/3}$
	Desert, Clear Weather	10^{-12}	
	Any Terrain, Adverse Weather	10^{-14}	C_n^2 (3 m) $(h/3)^{-2/3}$
	Over Water, Any Weather	10^{-15}	C_n^2 (3 m) $(h/3)^{-2/3}$
Night	Any Terrain, Any Weather	10^{-14}	C_n^2 (3 m) $(h/3)^{-2/3}$
	Over Water, Any Weather	10^{-15}	

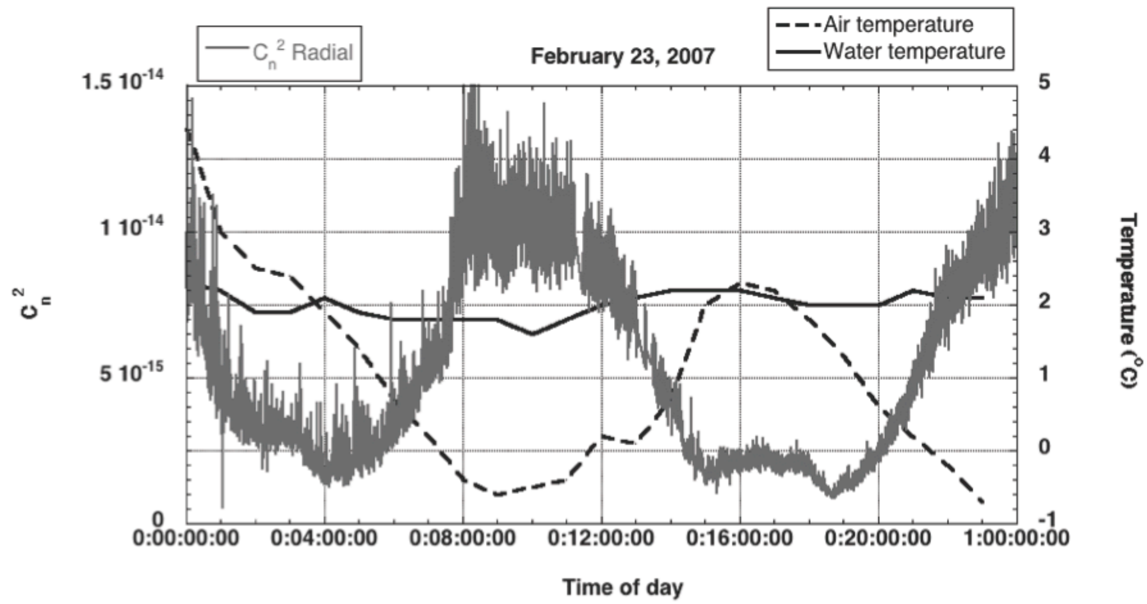

Figure 15. Refractive index structure as a function of air-water difference (From Naval Research Laboratory 2010)

D. WAVEFRONT ABERRATION

The wavefront of the laser beam propagating through atmospheric turbulence would become aberrated. As a result of the wavefront aberration, the intensity distribution of the laser beam would be adversely affected. For an ideal light beam with no wavefront aberration, the wavefront should be flat and the beam intensity should be evenly distributed; however, with turbulence, the wavefront is distorted, resulting in inconsistency in beam focusing, as shown in Figure 16. The uneven distribution of the light intensity shifts the focusing point on the detecting sensor and reduces the effectiveness of the communication system receiver to track the incoming light beam.

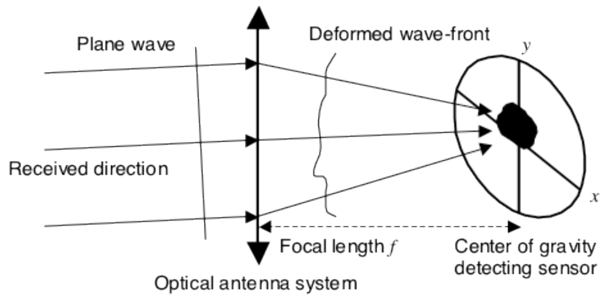

Figure 16. Wavefront aberration resulting in inconsistency in beam focusing (From National Space Development Agency of Japan, Tsukuba Space Center 2001)

Wavefront aberration leads to a poor Strehl ratio. The Strehl ratio is a measure of the observed peak intensity of an aberrated wavefront at an image plane relative to the theoretical maximum peak intensity of a perfect wavefront. The Strehl ratio is commonly used as an indication of the quality of the data received. A Strehl ratio of unity would mean the received data's integrity is maintained perfectly, and the received data deteriorates as the Strehl ratio deviates from unity. In general, the acceptable Strehl ratio is 0.8. The Strehl ratio, *SR*, can be obtained from (Stotts 2010)

$$SR = \frac{1}{\left(1+\left(d/r_0\right)^{5/3}\right)^{6/5}} \tag{2}$$

where d is the diameter of the optical systems and r_0 is the Fried parameter.

The Fried parameter or turbulence coherence length, r_0, is a measure of the optical quality of the atmosphere. It is an important parameter for describing the degree of turbulence in the atmosphere in terms of the aperture size (Saha 2011). The Fried parameter is calculated as

$$r_0 = \begin{cases} \left[0.423k^2 \sec(\beta)\int_0^L C_n^2(z)dz\right]^{-3/5} & \text{(for plane waves)} \\ \left[0.423k^2 \sec(\beta)\int_0^L C_n^2(z)\left(\frac{z}{L}\right)^{5/3} dz\right]^{-3/5} & \text{(for spherical waves)} \end{cases} \tag{3}$$

where k is the optical wave number, β is the angle of the telescope measured from the zenith, L is transmission path length and z is the transmission altitude.

For electromagnetic wave transmission along a horizontal path, the Fried parameter for plane and spherical waves reduces to

$$r_0 = 1.68(C_n^2 L k^2)^{-3/5} \text{ (for plane waves)}$$

(4) $r_0 = 3(C_n^2 L k^2)^{-3/5}$ (for spherical waves) (5)

E. BEAM BROADENING AND BEAM WANDER

Beam broadening refers to the widening of a beam that exceeds the expected diffraction limit as the light beam travels through the turbulent atmosphere. The diffraction limit is the minimum angular separation of two light sources that can be differentiated by a telescope. The diffraction limit is dependent on the wavelength of the light source being observed and the diameter of the telescope (Tyson 1998). Beam broadening could cause the beam intensity to drop below a required threshold and results in loss of signal. Atmospheric turbulence can also lead to beam wandering (random movement) in which the laser beam falls onto the receiver off-centered. Beam wandering could pose a problem for communication links because the ATP system would have difficulties acquiring and tracking the wandering beam. The received power would be reduced as a result of beam wandering. The random point of maximum irradiance is termed as “hot spot” (Andrews 2006) and is illustrated in Figure 17a. In Figure 17b, the shaded circles depict the short-term random motion of the light beam on the receiver plane. The long-term impact of beam wandering results in the formation of the larger outer circle on the receiver plane called the long-term spot size.

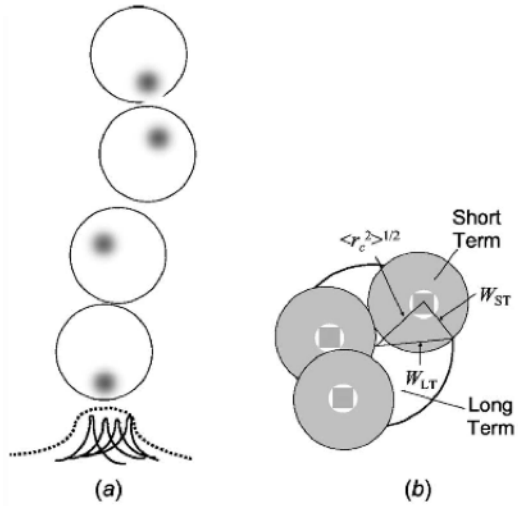

Figure 17. (a) Beam wander as described by movement of “hot spot” within the beam. (b) The long-term effect of beam wander (From Andrews 2006)

F. SCINTILLATION

Scintillation is the fluctuation in the signal irradiance caused by atmospheric turbulence. The scintillation index (normalized variance of the irradiance fluctuation), σ_1^2, is used widely to describe this intensity fluctuation effects. For weak fluctuation regime (scintillation index less than 1), the scintillation index is proportional to the Rytov variance of a plane wave, which is given by

$$\sigma^2{}_1 = 1.23 C^2{}_n k^{7/6} L^{11/6} \tag{6}$$

where C_n^2 is the refractive index structure, k is the optical wave number, and L is the transmission path length.

The scintillation index increases as Rytov variance increases until it reaches a maximum value larger than 1 in the random focusing regime. This regime is known as random focusing regime because the beam focusing reaches its maximum effect caused by large-scale inhomogeneities. As C_n^2 and/or L increase, the beam focusing effect is weakened as a result of laser beam phase incoherency resulting in multiple self-interference and its peak intensity begins to drop. The multiple self-interference effect reduces the coherency of the beam as it propagates and, eventually, the beam appears like multiple independent sources with random phases, causing the beam's irradiance to fluctuate (Andrews 2001). The fluctuating of the beam's irradiance results in lower received power.

G. LINK BUDGET

The link budget is a computation of electromagnetic wave's power to determine whether the electromagnetic wave has enough energy to be transmitted to a receiver. The bit error rate (BER) requirement, system losses and atmospheric losses are also taken into considerations during link budget computation. The BER is the ratio between the number of bits in error and the total number of bits sent and, intuitively, it is most desired for the BER to be as low as possible. Pointing and matching losses are system losses that could cause vibrations and electrical noise in the ATP system. The impact of vibrations and electrical noise is the random fluctuations of the transmitted beam. Atmospheric losses include atmospheric absorption, scattering and turbulence. Atmospheric losses can result in degradation in the quality of the beam such as unfocussed beam or reduction in beam intensity. Therefore, it is necessary to perform a budget computation that accounts for the known losses attributed by the communication subsystems and the varied atmospheric losses to ensure that there is adequate link margin to meet the availability of the communication system. The link equation (Nelson 2004) for computing the average power at the receiver, P_R, is given as

$$P_R = P_T\left[\frac{\pi D_T}{\lambda}\right]^2\left[\frac{\pi D_R}{\lambda}\right]^2\left[\frac{\lambda}{4\pi R}\right]^2\eta_T \exp\left[-\left(\frac{4\pi\sigma}{\lambda}\right)^2\right]\exp\left[-8\left(\frac{\theta_T}{\theta_{div\_T}}\right)^2\right]\eta_R L_{PR} L_{MM} L_{Atm} \tag{7}$$

where

P_T : Average transmitted power (W)

λ : Wavelength (m)

D_T: Transmitter aperture diameter (m)

D_R : Receiver aperture diameter (m)

R : Range between transmitted and receiver (m)

η_T : Transmitter optical efficiency

σ : Root mean square (RMS) wavefront error

θ_T : Transmitter angle w.r.t beam center (rad)

θ_{div_T} : Transmitter divergence angle (rad)

η_R: Receiver optical efficiency

L_{PR}: Receiver pointing loss (W)

L_{MM}: Mode matching loss (W)

L_{Atm}: Atmospheric loss (W)

The terms in (7) represent the power gains and losses; the losses are associated with the laser beam propagation and the lasercom system. Regarding the power gains, the terms $\left[\frac{\pi D_T}{\lambda}\right]^2$ and $\left[\frac{\pi D_R}{\lambda}\right]^2$ are the transmitter and receiver optical antenna gains. They are inversely proportional to the wavelength of the signal and directly proportional to the aperture diameters of the transmitter and receiver respectively.

The losses related to laser beam propagation are expressed by $\left[\frac{\lambda}{4\pi R}\right]^2$, which represents the free space propagation loss, $\exp\left[-\left(\frac{4\pi\sigma}{\lambda}\right)^2\right]$, which represents the Strehl ratio loss, and L_{Atm}, which is a loss collectively caused by atmospheric absorption, scattering and turbulence. The free space propagation loss is the loss in power as the beam moves through free space, without taking environmental effects into considerations. The free space propagation loss also does not include losses from non-ideal system specifications or system mismatch. The Strehl ratio loss refers to the power loss from the maximum peak intensity of a perfect planar wavefront.

The system-related losses are the transmitter pointing error loss, the receiver pointing loss, L_{PR}, and the mode matching loss, L_{MM}. The transmitter pointing error loss, $\exp\left[-8\left(\frac{\theta_T}{\theta_{div\_T}}\right)^2\right]$, is the amount of power loss caused by imprecise pointing and accounts for the difference between the peak power of the beam and the power at off-pointed location. A large misalignment between the transmitter angle and the beam center results in a large pointing loss. In addition, a narrower beam has a smaller divergence angle and, thus, a large misalignment would result in higher power loss. The receiver pointing loss accounts for the misalignment between the transmitter and receiver, which causes the beam to reach the receiver off-centered. Local jitters/vibrations of the receiver system can cause non-ideal reception of signal and increase L_{PR}. The mode matching loss defines the loss caused by imprecise spatial matching or coupling of the laser beams. By using heterodyne detection of the laser signal or ensuring perfect coupling of the laser beam into an optical fiber, mode matching losses can be avoided. The receiver optical efficiency, transmitter optical efficiency, Strehl ratio loss, transmitter pointing error loss, receiver pointing error loss, mode matching loss and atmospheric loss are also collectively known as the implementation loss.

H. WAYS TO INCREASE RECEIVED POWER

There are several ways in which the received power could be increased (Chien n.d.). First, the most direct way to increase the received power is to increase the transmitted power. However, increasing the transmitted power would mean increasing the system size, which, in turn, requires large space, increasing its operation cost, and dealing with attending thermal issues.

Second, increasing the aperture size of the transmitter effectively reduces the beamwidth and, thus, improves the performance of the system. However, increasing the aperture would increase the size of the system and would occupy a large area on the platform. The drawback of reducing the beamwidth would be the need to improve tracking and pointing accuracy so that the receiver is able to precisely receive the transmitted laser beam.

Third, increasing the aperture size of the receiver improves the receiver gain. However, this method would also increase the size of the system and occupy more space on the platform. Therefore, increasing the aperture size of the receiver would not be an optimal solution for small platform. Furthermore, widening the receiver's aperture could potentially increase the background noise level.

Fourth, the use of small wavelengths improves the optical gain for both the transmitter and the receiver. A beam with a shorter wavelength also reduces the impact of wavefront aberration and thereby reduces Strehl ratio losses. However, there is a limitation to reducing the wavelength because of the wavelength-dependent atmospheric absorption.

Fifth, reducing the receiver pointing and mode matching losses could also increase the received power. The receiver pointing losses could be reduced by precise calibration and alignment between the transmitter and receiver. Mode matching losses could be minimized by improving the spatial matching/coupling of the laser beams.

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IV. BIT ERROR RATE AND SNR CALCULATION

This chapter defines BER and E_b / N_0, discusses the relationship between them and the modulation techniques considered in this thesis, and explains the calculation of SNR corresponding to a link budget and the different components contributing to it. E_b / N_0 is the ratio between the energy per bit and the noise power spectral density. The modulation techniques are the M-ary orthogonal modulation technique and multiple phase M-ary modulation technique.

A. BER VS E_B/N_0 PLOT

BER is one of the figures of merit used to assess the quality of a communication system. As a stream of data is sent from its transmitter to a receiver through a medium, there is a possibility that errors will be introduced into the signal and, thereby, affect the integrity of the data received. BER is calculated using the error function, given the energy of each bit, E_b (J/bit), and the noise spectral density, N_0 (W/Hz). The SNR is linked to the E_b / N_0 by the equation

$$SNR = \left(E_b / N_0\right)\left(R_b / BW\right) \tag{8}$$

In which the bit rate, R_b, refers to the number of bits processed per unit time (Sklar 2001).

BER is used interchangeably with the bit error probability, $P_B(M)$. A $P_B(M)$ vs. E_b / N_0 plot provides information on the minimal E_b / N_0 required to achieve a $P_B(M)$ for a specific modulation technique. Figures 18 and 19 display the graphs of $P_B(M)$ as a function of E_b / N_0 for, respectively, a coherently detected M-ary orthogonal modulation technique and a coherently detected multiple-phase M-ary modulation technique. M-ary refers to M numbers of symbols to be produced by the modulator, in which $M = 2^k$ and k represents the number of bits the processor uses. If three bits are used for modulation, a total of 8 symbols will be produced. As indicated by Figure 18,

$P_B(M)$ increases with increasing k, given a fixed E_b / N_0. Figure 19 indicates the opposite. The reason for the difference is that, for the coherently detected M-ary orthogonal modulation technique, the BW increases with increasing k, whereas, for the coherently detected multiple phase M-ary modulation technique, the BW remains constant.

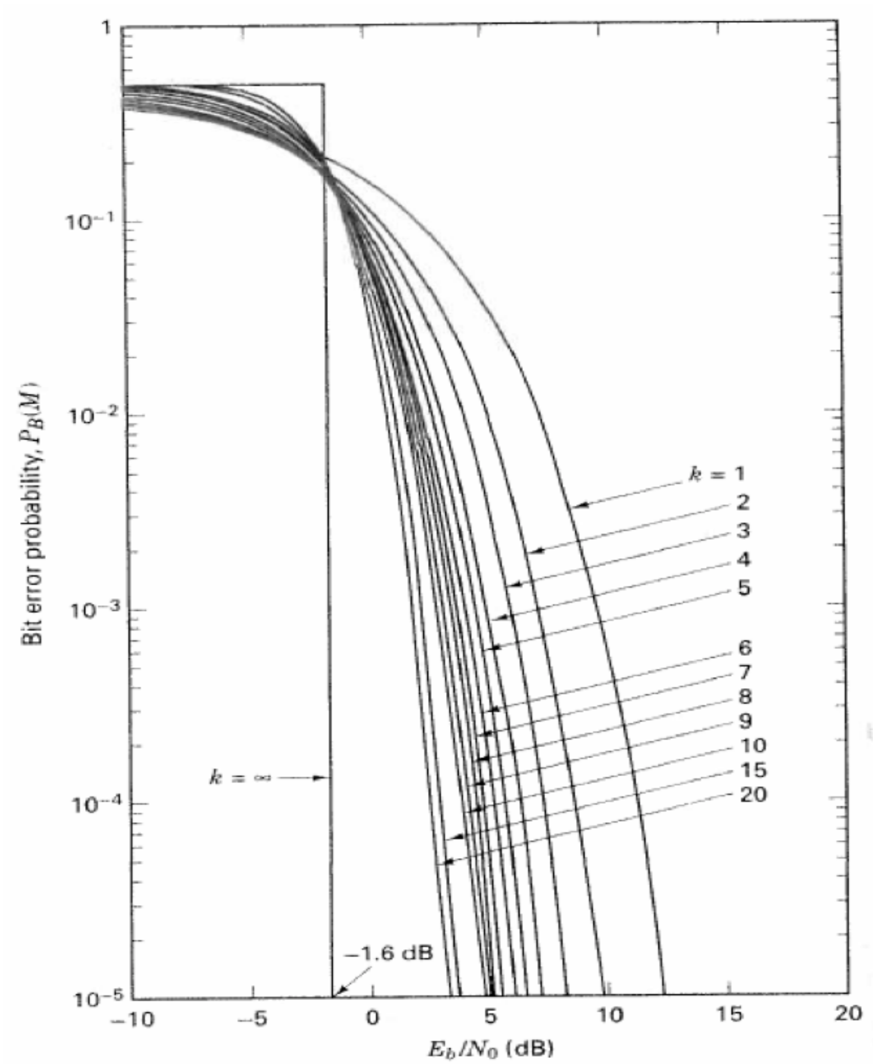

Figure 18. $P_B(M)$ vs E_b/N_0 plot for a coherently detected M-ary orthogonal modulation technique (From Sklar, 2001)

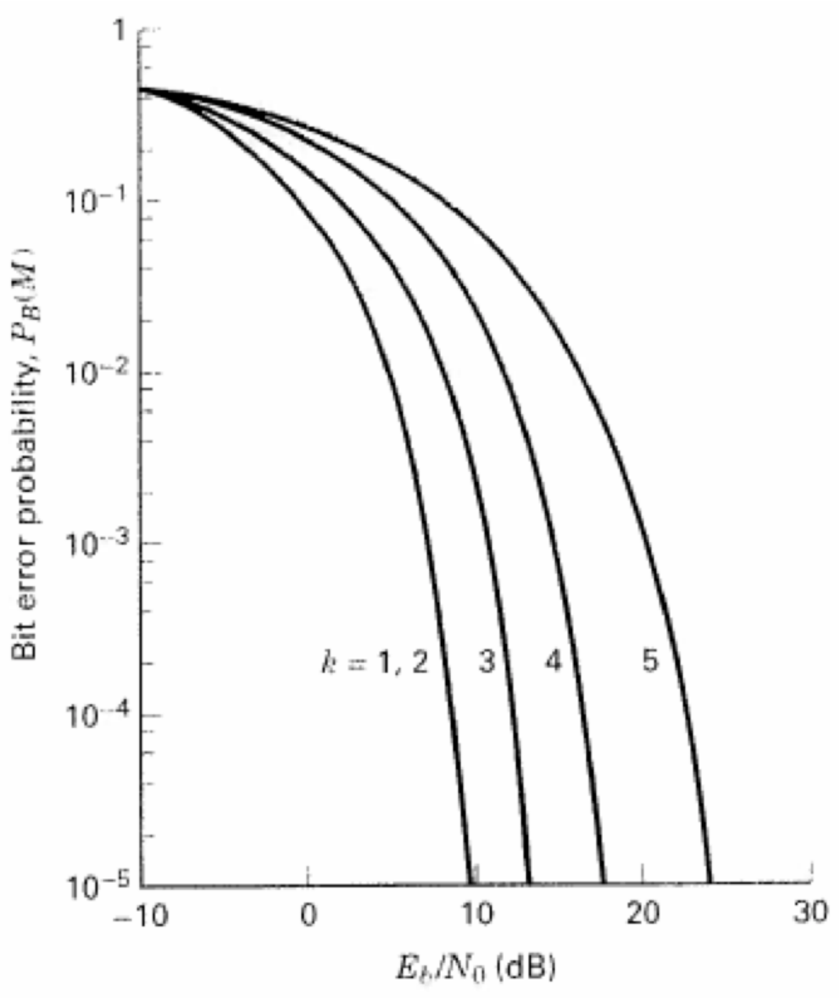

Figure 19. $P_B(M)$ vs E_b/N_0 plot for a coherently detected multiple phase M-ary modulation technique (From Sklar, 2001)

In the coherently detected M-ary orthogonal modulation case, BW is thus traded for performance. In the coherently detected multiple phase M-ary modulation case, in which more symbols are transmitted using the same BW, the probability of intersymbol interference (ISI) is higher, and so is the ambiguity of each symbol. Different modulation techniques can, thus, be considered when balancing between the available BW, power requirement, system cost, complexity, and data throughput. In essence, once the BER requirement is established, a modulation technique is selected based on resources available to produce the required E_b / N_0 (Sklar 2001).

B. SNR CALCULATION

With the received power, P_R, obtained from the link budget calculation in Chapter III, the SNR at the receiver is determined according to (Nelson 2004)

$$SNR = \frac{n_{slot}}{NF\left(1+\frac{P_B}{P_R}\right)+\frac{I_{dark}}{e\eta\frac{P_R}{h\nu}}+\frac{2k_{Boltz}T_{eff}R_L h}{e^2G_R^2\eta P_R\nu}} \tag{9}$$

where

n_{slot} : Number of photons per time slot

NF : Excess noise factor

P_B : Background power (W)

I_{dark}: Dark current (A)

e : Electron charge (C)

η : Quantum efficiency

h : Planck’s constant (Js)

ν: Spectral frequency (Hz)

k_{Boltz}: Boltzmann’s constant (J/K)

T_{eff}: Effective noise temperature of load resistor (K)

R_L: Load resistance (Ω)

G_R : Receiver gain

The number of photons per time slot, n_{slot}, impacting on the detector is given by

$$n_{slot} = \frac{\eta \log_2 M P_R \tau}{h\nu} \tag{10}$$

where M is the number of possible time slots and τ is the slot duration.

In Chapter V, (9) is used to determine the SNR related to the link budget obtained for the ship-to-ship lasercom scenario at hand.

V. ILLUSTRATION OF LASERCOM LINK BUDGET CALCULATION AND DISCUSSION OF TRADEOFF ANALYSIS RESULTS

The purpose of this chapter is to illustrate the link budget computation for lasercom in a search-and-rescue mission carried out in a light-haze maritime environment by two Navy ships in an area of 25-km radius in which video images and voice commands are sent to and fro the ships. In this chapter, a parametric analysis is also performed to ensure the satisfaction of the SNR required for achieving the desired voice and video quality.

A. LASERCOM PERFORMANCE REQUIREMENT AND ASSUMPTIONS

In this search-and-rescue mission, video images and voice commands are transmitted at 1.5 Mbps (video compact disc (VCD) quality using moving picture expert group 1 (MPEG1) compression (Pan 1995)) with a 10^{-9} BER. This BER, which is appropriate for data rates exceeding 100 Mbps, is chosen because it represents the most stringent requirement (i.e., the worst case scenario for this mission) (Nelson 2004).

To establish the SNR required for achieving the desired voice and video quality, a modulation technique is selected, a transmission BW is specified, and a link margin is assumed. First, the quadrature phase shift keying (QPSK) modulation technique is chosen. It is a coherently detected multiple-phase M-ary modulation technique, in which the modulating signal shifts the carrier signal's phase into four different states. Each state represents a symbol and contains two bits of information. Transmitting a symbol thus means transmitting two bits simultaneously. As such, QPSK is a popular modulation scheme in wireless systems because it reduces the required transmission bits rate and bandwidth (Chitode, 2007). Second, the transmission BW is chosen to be equal to R_b; it then follows from (8) that $SNR = E_b / N_0$. From Figure 20, for a 10^{-9} BER, $\left(E_b / N_0\right)$, or the SNR in this case, corresponding to the selected QPSK modulation is approximately 13 dB. Third, given the maritime environment in which the mission is carried out, an additional link margin of 5 dB can be reasonably chosen to be added to the link budget to compensate for other forms of unforeseeable degradations to the transmission light beam. Therefore, the minimal SNR, denoted by SNR^*, required to meet the required video and voice quality is 18 dB.

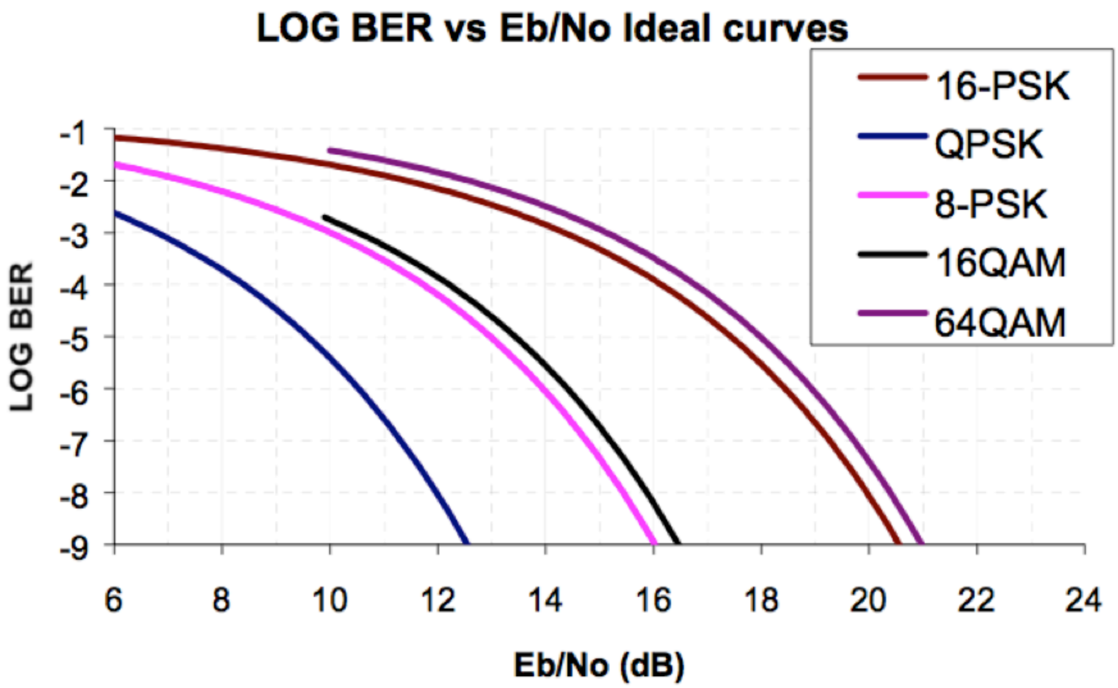

Figure 20. BER vs Eb/N_0 curves for different modulation techniques (From Langton 2004)

B. SCENARIO, OPERATION, AND SYSTEM PARAMETERS FOR SEARCH AND RESCUE MISSION

In this illustration, the parameters pertaining to the scenario and operation and the lasercom system employed in this search-and-rescue mission are provided in Tables 8 and 9, respectively. Table 10 shows the calculated parameters. Three specific parameters that can be adjusted in order to support the mission are the transmission height, the average transmitted power, and the transmitter aperture size. In the baseline configuration considered in this thesis, the transmission height, the average transmitted power, and the transmitter aperture size are chosen to be 30 m, 20 mW, and 0.1 m, respectively.

Table 8. Scenario and operation parameters for search-and-rescue mission

Scenario Parameters	
Transmission height (transmit and receive antennas are mounted at 30 m above the water surface)	30 m
Visual range corresponding to a light-haze maritime environment	10 km
Atmospheric loss, L_{Atm}	5×10^{-3}
Range (maximum range for the ships to communicate with one another), R	50 km
Bit rate, R_b	1.5 MHz

Table 9. System parameters for search-and-rescue mission

System Parameters	
Laser wavelength, λ	1.55 μm
Transmitter aperture diameter, D_T	0.1 m
Transmitter angle w.r.t beam center, θ_T	0 rad
Receiver aperture diameter, D_R	0.1 m
Average transmitted power, P_T	20 mW
Transmitter optical efficiency, η_T	1
Transmitter pointing loss, L_{PT}	0.5
Receiver optical efficiency, η_R	1
Receiver pointing loss, L_{PR}	0.5
Mode-matching loss, L_{MM}	1
Quantum efficiency, η	0.8
Number of possible time slots, M	4
Background power, P_B	10^{-16} W
Dark current, I_{dark}	2.5×10^{-9}A
Load resistance, R_L	50Ω
Effective noise temp of load resistor, T_{eff}	400 K
Gain, G	1
Excess noise factor, NF	10

Table 10. Calculated parameters for search-and-rescue mission

Wavefront loss (for plane wave)	0.317
Transmitter divergence angle, $\theta_{div\_T} = 1.22\dfrac{\lambda}{D_T}$	18.91 μrad
Transmitter antenna gain, G_T	4.11×10^{10}
Free space propagation loss, L_{FS}	6.09×10^{-34}
Receiver antenna gain, G_R	4.11×10^{10}
Gain across link, $G_L = G_T L_{PT} L_{FS} G_R L_{PR}$	4.05×10^{-6}
Number of photons per time slot, n_{slot}	3.37×10^{5}
Bit time, T_b	6.67×10^{-7}s
Slot duration, $\tau = \dfrac{T_b \log_2 M}{2^{\log_2 M}}$	3.33×10^{-7} s

C. SNR COMPUTATION AND TRADEOFF ANALYSIS

It follows from (7) and (9), respectively, that P_R is 8.1×10^{-8} W and SNR is 13 dB. The resulting SNR is thus 5 dB short of SNR^*. Certain parameters, such as the laser wavelength, the transmission height, the average transmitted power, and the transmitter aperture size, may be varied in order to achieve the SNR required to support the mission. As indicated by (7), P_R could be increased by selecting laser wavelengths smaller than 1.55 μm. Since the 1.55 μm wavelength falls into a window in which the atmospheric transmittance is close to one, such selections would result in severe attenuation caused by water vapor absorption. A tradeoff analysis is thus carried out to determine the appropriate values of the transmission height, the average transmitted power, and the transmitter aperture size. The discussion of the tradeoff analysis now follows.

Figures 21 shows that SNR increases with increasing transmitter aperture size and transmission height, with the average transmitted power remaining at 20 mW. The range of SNR that could be achieved based on a transmission height of 20 to 100 m and a transmitter aperture size of 0.1 to 0.26 m is approximately 11 to 35 dB. For the case at hand, in order to satisfy SNR^*, the transmission height must be greater than 100 m if the transmitter aperture size is kept at 0.1 m. The values of these parameters correspond to Configuration 1 in Table 11.

Figures 22 shows that SNR increases with increasing transmitter aperture size and average transmitted power (Avg Tx Power), with the 30-m transmission height. The range of SNR that could be achieved based on an average transmitted power of 10 to 90 mW and a transmitter aperture size of 0.1 to 0.26 m is approximately 7 to 40 dB. For the case at hand, in order to satisfy SNR^*, the transmitter aperture size of 1.4 m is needed if the average transmitted power is 20 mW. The values of these parameters correspond to Configuration 2 in Table 11.

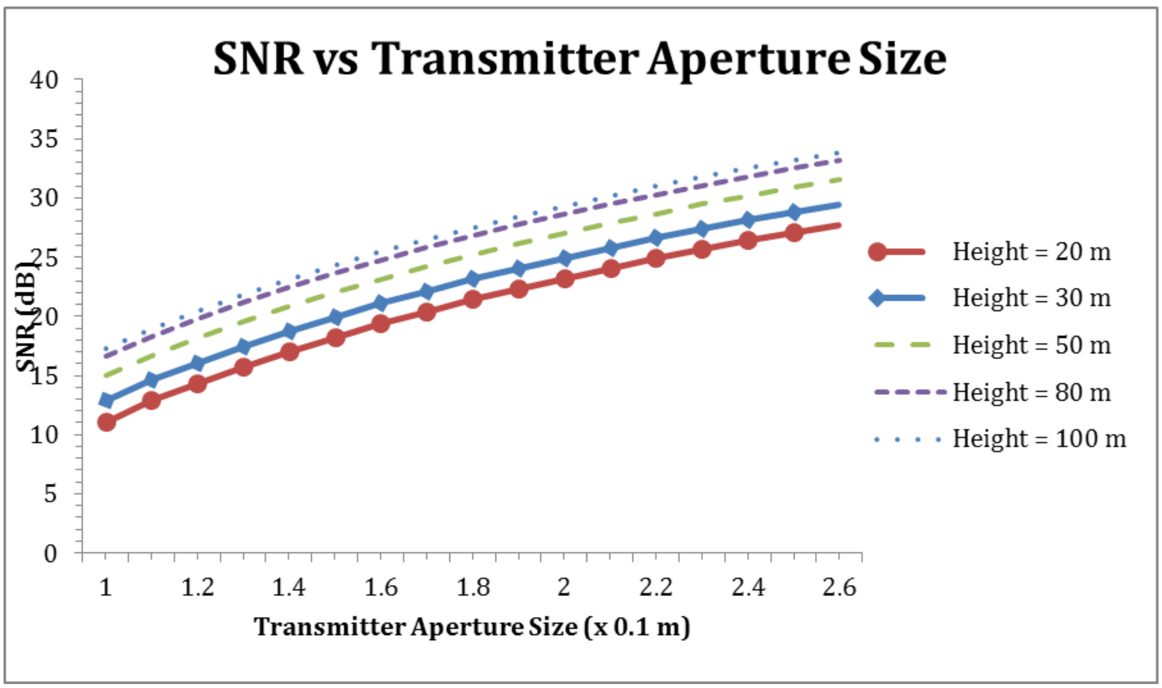

Figure 21. SNR vs. transmitter aperture size at various transmission height

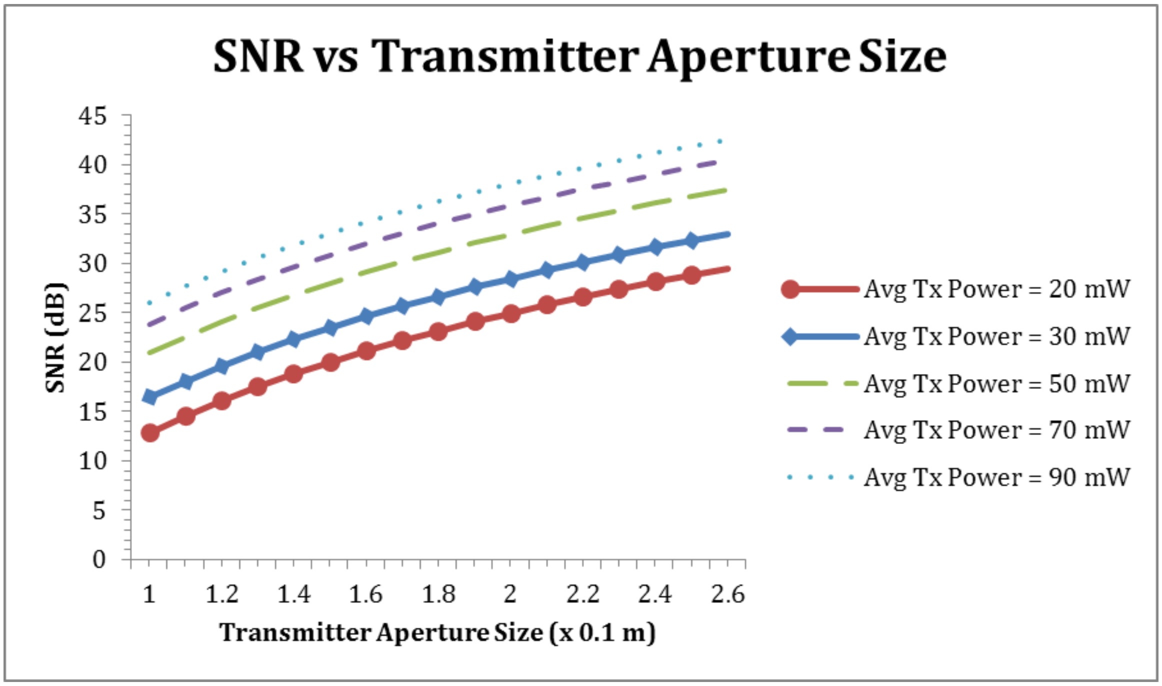

Figure 22. SNR vs. transmitter aperture size at various average transmitted power

Figure 23 shows that, with the transmitter aperture size of 0.1 m, SNR increases with increasing transmission height and average transmitted power. The range of SNR that could be achieved based on a transmission height of 20 to 100 m and an average transmitted power of 10 to 90 mW is approximately 5 to 30 dB. For the case at hand, in order to satisfy SNR^*, the average transmitted power must be above 40 mW if the transmission height is kept at 30 m. The values of these parameters correspond to Configuration 3 in Table 11.

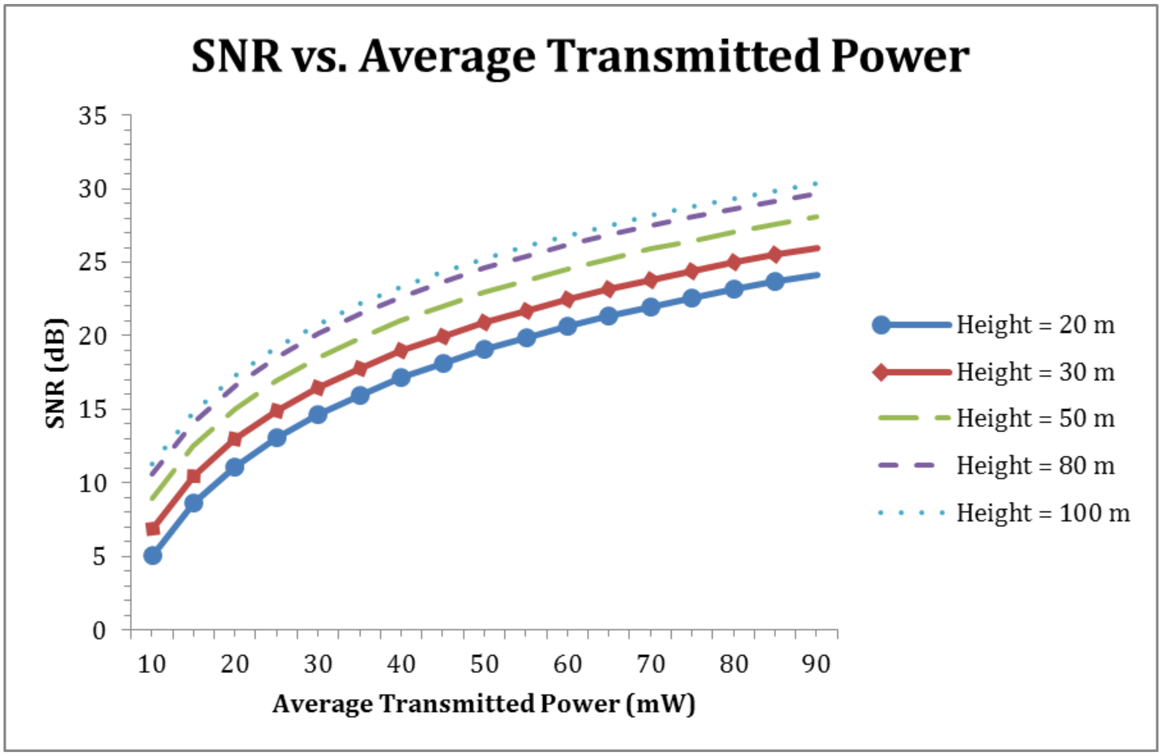

Figure 23. *SNR* vs. average transmitted power at various transmission height

Table 11 provides a summary of the parameters corresponding to the baseline configuration and the three configurations obtained in the tradeoff analysis.

Table 11. Configuration characterized by transmission height, transmitted aperture size and average transmitted power

	Configuration			
Parameters	Baseline	1	2	3
Average transmitter power (mW)	20	20	20	40
Transmitter aperture size (m)	0.1	0.1	0.14	0.1
Transmission height (m)	30	> 100	30	30

In conclusion, in this search-and-rescue mission, SNR^*, the minimal SNR to meet the required video and voice quality, is 18 dB. To satisfy SNR^*, hence to support the mission, certain lasercom system parameters must be appropriately selected. Since there is not much latitude in varying the laser wavelength, because of its interaction with the atmosphere leading to the beam attenuation, three parameters considered for tradeoff are the transmission height, the average transmitted power, and the transmitter aperture size. In the example calculation of the link budget, in which the transmission height is 30 m, the average transmitted power is 20 mW, and the transmitter aperture size is 0.1 m, the resulting SNR of 13 dB does not satisfy SNR^*. A tradeoff analysis is then carried out to determine the values of these parameters that support the mission. The results of the tradeoff analysis indicate that, at the transmission height of 30 m, there are two options: (1) keep the average transmitted power at 20 mW, but increase the transmitter size to 0.14 m; and (2) keep the transmitter size of 0.1 m, but increase the average transmitted power to 40 mW. In the first option, the slight increase in the transmitter aperture size would not create a space issue for the ship; a small increase in weight, which is expected, would not be an issue for the ship either. In the second option, an increase in the average transmitted power is a direct solution, but excessive heat generated could adversely affect the optical elements of the ATP system, thereby degrading its performance. In addition, additional cooling mechanisms would be required, which would inflate the system acquisition and maintenance cost. The first option would, therefore, be the preferred solution.

Finally, the three parameters—the transmission height, the average transmitted power, and the transmitter aperture size—yield all possible options or combinations. Figures 21–23 can be used to determine the combinations that would satisfy the required SNR.

VI. CONCLUSION

The objective of this research is to provide insights into effects of maritime environment on lasercom link budget, thereby supporting ship-to-ship lasercom system design and mission planning. This chapter summarizes and underlines the key points discussed in the thesis regarding lasercom systems and lasercom link performance under different maritime environmental conditions.

A. LASER COMMUNICATIONS

With the rapid growth in communications and information domain, there is an inexorable need for the ever-increasing bandwidth for high-speed data transmissions. The current RF communication technologies can transmit data only in the Mbps region, and the answer for high-speed data transmissions would be to adopt lasercom, in which the data transmission rates are in the Gbps region. Besides offering higher data rates, lasercom also provides better security as compared to RF communications. The narrower beamwidth of a laser beam provides better LPI and LPD; reduces the probability of signal jamming from an adversary; and allows frequency reuse whereby two users can operate at the same frequency without interference. Compared to RF communications, laser communications are far superior in speed, in bandwidth efficiency, and in security for data transmissions. The move to switch from RF communications to laser communications for next-generation communication networks is imminent.

B. CHALLENGES FOR LASER COMMUNICATIONS

Laser communications face a number of challenges. First, the motion of platforms on which lasercom systems are mounted affects the laser beam stability. Given the laser beamwidth of the order of microradians, a slight movement in either of the communicating platforms will result in the off-center pointing of the laser beam. Therefore, it is crucial that the ATP system has the capability to localize the communicating platforms through high-speed feedback systems. The ATP system also has to be equipped with an IMU and a gimbal system that could respond rapidly and precisely to changes in its hosting platform position. Second, a laser beam propagating in the atmosphere can be severely degraded by atmospheric scattering, absorption, and turbulence. An adaptive optics system as a part of an ATP system is needed to mitigate the beam degradation. The capabilities of the ATP and adaptive optics systems to compensate for laser beam attenuations and platform random motions are the cornerstones for lasercom. Finally, frequent vessel traffic in some operating environment could obstruct transmitting and receiving lasercom systems, thereby preventing communications between the two systems.

C. LINK BUDGET

A link budget analysis represents a systematic method to determine whether the energy of a signal is adequately transmitted to a receiver. The link budget takes into consideration the propagation and implementation losses. By performing a link budget analysis, a lasercom system designer is able to analyze and trade the various factors or parameters contributing to a link budget that meets a required SNR.

The link budget computation for ship-to-ship laser communications is illustrated with a search-and-rescue mission carried out in a light-haze maritime environment by two Navy ships in an area of 25-km radius in which video images and voice commands are sent to and fro the ships at 1.5 Mbps (video compact disc (VCD) quality using MPEG1 compression) with a 10^{-9} BER. The SNR required for achieving the desired voice and video quality is 18 dB, assuming a link margin of 5 dB and the use of the QPSK modulation technique.

The tradeoff analysis to determine the values of the parameters − the transmission height, the average transmitted power, and the transmitter aperture size – that would satisfy the required SNR, hence support the mission, indicates that, at the desired transmission height of 30 m, the baseline configuration of 0.1-m transmitter aperture size and 20-mW average transmitted power results in a 15-dB SNR, thus failing to satisfy the required SNR, whereas both the configuration of 0.14-m transmitter aperture size and 20-mW average transmitted power and the configuration of 0.1-m transmitter aperture size and 40-mW average transmitted power support the mission. There are other possible configurations that might satisfy the required SNR, but the latter two configurations reflect only a slight change from the baseline configuration. A major change from the baseline configuration implies a large increase in the transmitter aperture size and average transmitted power. Such increase goes against system design objectives as large apertures require large space and add weight and high power generates excessive heat which adversely affect the optical elements of the ATP system, thereby degrading its performance, not to mention that additional cooling mechanisms are needed and, consequently, will inflate the system acquisition and maintenance cost. In light of this system design consideration, the configuration of 0.14-m transmitter aperture size and 20-mW average transmitted power would be the preferred solution.

Finally, Figures 21–23 could be used to determine all possible configurations that would satisfy the required SNR.

D RECOMMENDATIONS

The link budget computation assumes that the ATP subsystems perform "perfectly," and errors caused by platform dynamics are not considered. Future work should incorporate the communicating platforms' motions at different sea state levels in the link budget computation. Furthermore, future research should explore ATP system options that minimize the adverse effects of maritime environmental conditions on lasercom SNR.

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